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SATELLITE LINKS FOR TELEVISION CONTRIBUTION:

Reception requirements for links using transportable transmitting earth stations

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THE BRITISH BROADCASTING CORPORATION

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SATELLITE LINKS FOR TELEVISION CONTRIBUTION: RECEPTION REQUIREMENTS FOR LINKS USING TRANSPORTABLE TRANSMITTING EARTH STATIONS

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Summary

The BBC operates a number of transportable satellite earth stations for linking Television and Radio Outside Broadcasts back to studio centres without the need for multiple-hop terrestrial links. Usually they are operated with an EBU-leased transponder in a Eutelsat satellite, and receiving facilities are provided by British Telecom International at their Madley earth station. There are disadvantages in this arrangement and one possible solution may be to establish a receiving earth station near to, or within BBC premises in London.

Whilst examining the requirements for such a receiving station, the item of greatest concern has been the diameter of the receiving antenna. As well as providing theoretical predictions it was decided that Research Department should, with the help of Television Outside Broadcasts, conduct a series of practical tests using existing earth stations with antennas of around the predicted, required diameter.

These tests were carried out simultaneously at two earth stations in Copenhagen and Baldock during the period 12th to 14th September 1989, and the methods of testing and the results are presented in the Report. Some more detailed but general background information is also given about the mode of operation of the satellite transponder and the factors which affect the performance of a receiving earth station.

It is concluded that that an antenna of around 10 m diameter will be needed to achieve a generally useful level of performance when using the EBU-leased transponder. It is also concluded that neither of the existing earth stations used in the tests offers sufficient performance to meet current BBC requirements.

Index terms: *Satellites; TV links; SHF; PAL reception; antenna-Rx; comparison; field tests*

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SATELLITE LINKS FOR TELEVISION CONTRIBUTION: RECEPTION REQUIREMENTS FOR LINKS USING TRANSPORTABLE TRANSMITTING EARTH STATIONS

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SATELLITE LINKS FOR TELEVISION CONTRIBUTION: RECEPTION REQUIREMENTS FOR LINKS USING TRANSPORTABLE TRANSMITTING EARTH STATIONS

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1. INTRODUCTION

The BBC operates a number of transportable satellite earth stations, and these are proving to be of great value for linking Television and Radio Outside Broadcasts (OBs) back to studio centres without the need for multiple-hop terrestrial links. Usually they are operated with a transponder in the Eutelsat I-F2 satellite, one of a pair of transponders which are leased permanently to the EBU. Receiving facilities are usually provided by British Telecom International (BTI) at their Madley earth station.

There are disadvantages in this arrangement, and one possible solution may be to establish a receiving station near to, or within BBC premises in London. For Radio Outside Broadcasts a 3 m receiving earth station was installed on the roof of London Broadcasting House in June 1989, and this has been used successfully for a season of Radio 1 Road Shows. There are obvious attractions to establishing a receiving earth station at Television Centre for Television Outside Broadcasts.

A group has been set up, within the BBC, to examine the requirements for such a station, and the item of greatest concern has been the diameter of the receiving antenna. The existing BTI station at Madley station has an antenna of 18 m diameter, but, aside from the cost, Madley is in open countryside and the assembly of such a large structure on or near a BBC site in London could not be contemplated for planning reasons. The argument for finding a suburban site with more space is defeated by the complications (and potential degradations) introduced by a terrestrial link.

Therefore, attention has turned to the question of what practical use could be made of a receiving earth station using an antenna significantly smaller than 18 m diameter. The hope is that a suitable antenna could be mounted on the roof of Television Centre.

It is very difficult to give a simple, clear answer to this question because so many contributory factors are involved; the characteristics of the BBC transportable earth stations, where they are likely to be operated, the characteristics of the satellite transponder (and any other transponders or satellites that we may use subsequently), the characteristics of the receiving earth station, and the propagation conditions that may be encountered on the up-link and down-link paths, to and from the satellite, mainly with respect to rainfall. Also, there was not a clear quality criterion, such as a minimum carrier-to-noise (C/N) ratio for a given percentage of time.

In general, smaller antennas lead to lower quality signals with an increased probability that adverse weather conditions, such as heavy rainfall, will lead to significant degradation or loss of the signals.

In principle, if values are known or assumed for all other contributory factors in the satellite link, the effect of varying only the size of the receiving earth station antenna can be found using link budget calculations. However, in view of the major cost of building such a station there really is no substitute for practical tests using existing stations with antennas of appropriate sizes, if only to establish the real values for factors whose values would otherwise have to be assumed.

To this end, a series of such tests was carried out during the period 12th to 14th September 1989, using simultaneously two existing receiving stations at Copenhagen (in Denmark) and Baldock (in England). In this Report, these tests are described and the results are presented.

Earlier, theoretical work at Research Department had shown that an antenna diameter of about 10 m, giving a G/T of about 36 dB/K, would be a suitable compromise between usefulness and practicality.

2. BACKGROUND INFORMATION

Before the tests are described in detail, some more general background information will be given about satellite links and the way that the EBU-leased transponders are operated, for the benefit of readers who may not be fully acquainted with this subject.

In the following section the satellite will be described as though it carried only one transponder, whereas in practice the Eutelsat I has facilities for twelve. Also, consideration will only be given to the operation of the transportable earth station in Great Britain, whereas in practice, operation anywhere in Europe would be desirable, although this might not be practicable.

2.1 Components of a satellite link

We are interested in the configuration shown in Fig. 1, where a transportable earth station is transmitting the up-link signal to the satellite at a frequency of about 14 GHz. The signal is received by a receiver within the satellite, its frequency is changed to about 11 GHz and then the down-link signal is transmitted back to earth. The combination of receiver, frequency changer and transmitter within the satellite is known as a transponder. The down-link signal is then received by the fixed receiving earth station which is the subject of these tests.

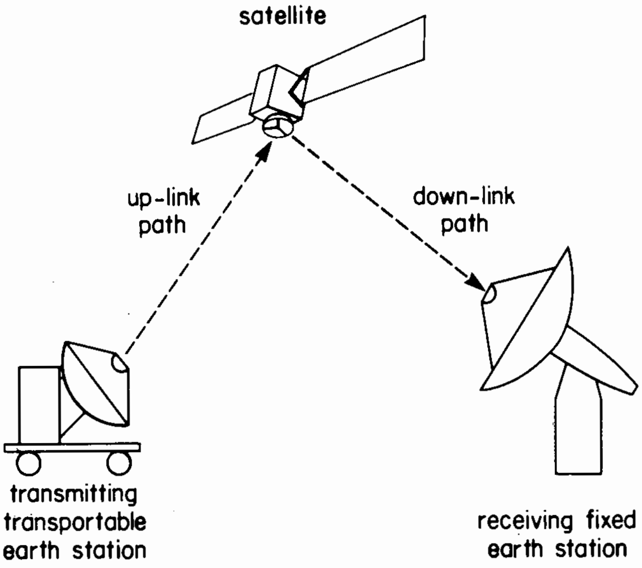
satellite
up-link path
down-link path
transmitting transportable earth station
receiving fixed earth station

Fig. 1 - Basic configuration of the satellite link.

Noise and other degradations are imposed on the signal during its passage between the earth stations, and in order to quantify the overall performance of the link it is useful to partition the link into two groups of factors; those which affect the up-link from the transportable to the satellite, and those which affect the down-link from the satellite to the receiving station.

The performance of the up-link depends principally on:

(a) the Effective Isotropic Radiated Power (EIRP) of the transmitting earth station;

(b) the propagation loss incurred on the up-link path;

(c) the Gain over noise-Temperature ratio (*G/T*) of the up-link receiver in the satellite.

The performance of the down-link depends principally on:

(d) the EIRP of the transmitter in the satellite;

(e) the propagation loss incurred on the down-link path;

(f) the *G/T* of the receiving earth station.

For factor (a), the BBC currently operates a number of transportable earth stations with maximum available EIRPs from 68 dBW up to about 75 dBW. In establishing a new receiving earth station, the hope would be that any one of these could be served, individually, when it was located (at least) anywhere in Great Britain. However, this is unlikely to be practicable since it is known, from practical experience, that even when the Madley 18 m station is used to serve the lower EIRP transportables the overall link performance can be marginal.

2.2 Characteristics of the satellite transponder

Both factors (c) and (d) above are affected by the radiation patterns of the satellite's antennas, and the beam-centre values are usually quoted. The EBU-leased transponders on board Eutelsat I use the same antenna for up- and down-links, and the radiation patterns are essentially the same 'Eurobeam' which covers Western Europe and North Africa[1]. Because of this 'tapered' beam, the locations of the transmitting and receiving earth stations affect the overall link performance. For example, the further the transmitting station is away from the Eurobeam-centre (which is actually located just South West of Sardinia) the lower is the effective *G/T* of the satellite's receiver, and the lower is the overall performance of the link. London and the South of England appear on the −1.4 dB contour of the Eurobeam, so the *G/T* of the satellite's receiver and the EIRP of its transmitter are both effectively 1.4 dB lower than the beam-centre values when consideration is given to up- and down-links from and to these locations.

The actual value of the satellite's *G/T* is determined by the gain of its Eurobeam antenna, which is intimately linked to the width of the beam, and the effective noise temperature of the earth, which is invariant (at least for the foreseeable future!), so there is little scope for improvement here with the general advance of satellite technology.

Factor (d) is further complicated because the Eutelsat transponders do not incorporate AGC. This means that the satellite's EIRP is dependent, to some degree, on the level of the up-link signal it receives. However, the relationship is not linear because the satellite's transmitter uses a Travelling-Wave Tube Amplifier (TWTA) which can be saturated. Therefore the amplitude characteristic of the TWTA and the overall gain of the transponder are other important factors.

The transponder gain is usually given by quoting the beam-centre Incident Power-Flux Density (IPFD) for saturation, and variation of the actual IPFD about this value is considered as 'input backoff'. Meanwhile, variation of the satellite's EIRP below its maximum, saturation value is considered as 'output backoff' and the TWTA amplitude characteristic can be plotted as the variation of output backoff with input backoff. This is illustrated in Fig. 2, using values measured by the Eutelsat organisation. Facilities are included within the satellite to allow the transponder gain to be varied from time to time, to compensate for aging of active devices such as the TWTA, but this feature is beyond our control.

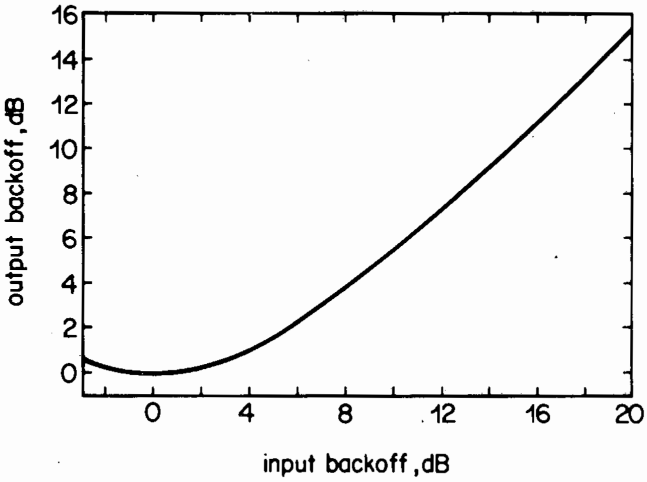

Fig. 2 - Eutelsat I-F2: Transponder 9 TWTA amplitude characteristic. Output backoff vs. input backoff.

2.3 Propagation losses

The propagation loss incurred on each of the up- and down-link paths (factors (b) and (e) in Section 2.1) comprises a large factor due to spherical spreading of the transmitted wave, a very small factor due to attenuation by atmospheric gases, and a small, but important factor due to attenuation caused by rainfall.

The spherical spreading factor is essentially constant because of the very large radius of the geostationary orbit in comparison with any potential re-location of either earth station within Great Britain. This has a value of 162.7 dBm^2 for the path between Eutelsat I-F2 and London, and this relates a transmitted EIRP (with units of dBW) to a received Power Flux Density (PFD, with units of dBW/m^2). It is often more useful to consider the effect of spreading in terms of the equivalent loss for transmission between two hypothetical, isotropic antennas (i.e. antennas with 0 dBi gain), but for this the value depends on the wavelength or frequency of the signal. The corresponding value for 11 GHz is 205.0 dB, and this relates a transmitted EIRP to a received signal power (both with units of dBW) for a receiving antenna gain of 0 dBi.

Gaseous attenuation (from oxygen and water vapour) can vary with the relative humidity, but its magnitude is so small that for our purposes it can be considered constant. At 14 GHz this factor contributes about 0.2 dB, and at 11 GHz about 0.1 dB.

Attenuation due to rainfall (and sometimes other precipitation, such as hail and snow) is not constant because it depends on the rate of precipitation, which, apart from expected seasonal variations, is a random process. It is small in terms of the number of decibels, but, in general, a satellite link possesses only a small margin to cope with additional losses; to do otherwise would be very costly.

Appropriate statistical methods for dealing with rainfall attenuation have been established within the CCIR[2], and these show, for example, that for the 11 GHz down-link path from Eutelsat I-F2 to Great Britain an attenuation of about 0.7 dB is probably only exceeded for 0.29% of the year, or 25.4 hours per year. Alternatively, this period can be re-stated as 1% of worst month (1% WM), so for 99% of the worst month the down-link rainfall attenuation will probably be less than 0.7 dB. This second form is often used when specifying the required performance of a satellite link (e.g. by the EBU[3]), giving a percentage of the worst month for which a particular level of service should (probably) be maintained. The corresponding attenuation for the 14 GHz up-link path is 1.1 dB.

In contrast, for the same down-link case during heavy rainfall, attenuations greater than 2.2 dB are likely to occur for up to 0.1% WM, which corresponds to 0.021% of the year, or 1.8 hours per year. On the up-link path, attenuations greater than 3.7 dB would be expected for this percentage of the year.

In principle any number of possible variations of the rainfall scenario can be dealt with by plotting results graphically, but practically it is often sufficient to consider one degree of rainfall, such as 1% WM conditions, as representing the 'faded' case. Additionally, the 'clear air' best case, when there is no rainfall attenuation, is a useful baseline for calculations, although in practice this level of performance is seldom achieved.

Since the overall performance of the link depends on the cascaded degradations of the up- and down-links, the weather conditions for the two propagation paths must be considered simultaneously. Usually, these will be uncorrelated, unless the transportable station is operated in the vicinity of the receiving station. This might occur during a test, but in normal programme operations, for such a short hop, a terrestrial link would usually be possible and less costly. Therefore, applying 1% WM rainfall conditions to both paths at the same time could give a pessimistic view of the achievable link performance. The expectation would be that in each year the 25.4 hour periods of rainfall attenuation greater than 1.1 dB on the up-link path, and greater than 0.7 dB on the down-link path, would be randomly distributed with little overlap; the validity of this obviously depends on the spacing of the two earth station locations. If the rainfall statistics for the two paths were truly uncorrelated the incidence of such overlapping fades would be the cumulative probability, which is the product, 0.00084% of the year, or less than four and a half minutes per year!

For want of a more rigorous approach, a simple way to consider the 'faded' case is to apply 1% WM rainfall attenuation to whichever of the up-or down-link paths has the greater effect on the overall link performance, and 'clear air' conditions to the other. The choice of which path to apply rainfall attenuation to depends on the balance between several parameters in the system.

Firstly, there is the difference between the magnitudes of the attenuations for 14 GHz (up-link) and 11 GHz (down-link) frequencies, for a given rainfall rate.

Secondly, the satellite transponder does not have AGC, as noted in Section 2.2, so attenuation on the up-link path can reduce the down-link EIRP transmitted by the satellite, thereby degrading the down-link *C/N* ratio as well as the up-link *C/N*.

Thirdly, rainfall attenuation can cause an increase in the effective noise temperature of the receiver at the end of an attenuated propagation path. The attenuation is caused partly by dissipation of power in raindrops, and partly by (non-dissipative) scattering. All forms of dissipative attenuator add noise to the signal being attenuated, and the magnitude of this noise power is a function of the effective noise temperature of the attenuating device, or medium, and its degree of attenuation. If the raindrops have a physical temperature of 290 K then an effective noise temperature of around 270 K accounts for the scattering.

This makes very little difference to the up-link receiver in the satellite because, as mentioned in Section 2.2, its antenna is directed towards the earth which has a noise temperature of around 290 K. Rainfall attenuation on the up-link path will add its own component of noise temperature, but will also reduce the noise power coming from the earth. The net result is, if anything, a very slight decrease in the noise temperature of the satellite receiver (because the rain appears 'colder' than the earth).

However, at the receiving earth station the antenna points towards the sky which, in the absence of rainfall, can have an effective noise temperature as low as 3 K (the 'cold sky' background, due to the 'big bang'). Therefore, rainfall attenuation on the down-link path always adds noise, degrading the *G/T* of the down-link receiver. The magnitude of this effect will be revealed in the next section. The effect on the received *C/N* ratio is twofold; the '*N*' (noise component) is increased, and the '*C*' (carrier component) is reduced by this attenuation.

Hence the choice of which path to apply the rainfall attenuation to has to be the result of some fairly detailed calculations, requiring knowledge of most of the system parameters which have fixed values.

In practical measurements, conditions other than 'clear air' introduce elements of loss which are not easily quantified without access to radiometers; devices for measuring the noise temperature, and thence the dissipative loss of a propagation path. Therefore, when interpreting test results a tolerance must be applied to account for the unknown rainfall attenuation, unless, of course, true 'clear air' conditions prevailed when the measurements were made.

2.4 *G/T* of a receiving earth station

The *G/T* ratio, or 'figure of merit' of a receiving earth station, gives an indication of how much noise will be added to the received signal before it is passed on (e.g. to a demodulator), and is therefore a useful guide to the station's performance. A large value of *G/T* corresponds to high performance, and this can be achieved using a large system gain, the '*G*' component, or a small system noise temperature, the '*T*' component, or a suitable combination of both[4].

The system gain comprises the antenna gain, which depends on the antenna diameter and its aperture efficiency, reduced by the elements of loss which attenuate the signal on its way to the Low-Noise Amplifier (LNA, the 'front-end' of the receiver); this includes non-dissipative losses such as that caused by mis-pointing of the antenna.

The system noise temperature accounts for the noise contributions from the antenna (as mentioned in Section 2.3 and further detailed in Appendix 1), from the LNA, and from all elements of dissipative loss which occur between the antenna and the LNA. In some cases noise contributions from receiver components downstream of the LNA also need to be accounted for in the *G/T*. These noise contributions are usually represented by equivalent noise temperatures, then the system noise temperature is the sum total of these.

Expressing the system gain in dB and the noise temperature in dBK (decibels with respect to 1 kelvin), the *G/T* then has units of dB/K. The method for calculating the *G/T* is detailed in Appendix 1, and this shows that, really, a single value cannot be given since the system noise temperature is influenced by rainfall attenuation. However, the 'clear air' value is often quoted, and this applies when there is no rainfall in the down-link path from the satellite.

Modern 11 GHz GaAs FET front-ends, working at room temperature, can offer noise temperatures as low as 100 K, and these are remarkably inexpensive when compared with the complicated parametric amplifiers and cryogenically cooled systems that were needed to achieve this performance ten years ago. There is little doubt that with advances in technology, manufacturers will be able to offer lower and lower LNA noise temperatures. However, there is a problem with relying on a very low-noise front-end to give a large *G/T*: as noted in Section 2.3, the onset of rainfall on the down-link path can degrade the *G/T* severely by raising the noise temperature of the receiving antenna.

A well designed receiving antenna can have a noise temperature in 'clear air' conditions of 50 K, or less. The sources of noise are mainly dissipative losses within its structure and sidelobe responses which point towards the 'warm' ground. When rainfall starts this increases; for example by about 40 K (giving a total of 90 K) when there is 0.7 dB down-link rainfall attenuation (1% WM conditions), and by about 107 K (giving a total of 157 K) when there is 2.2 dB attenuation (0.1% WM conditions). Using a 100K LNA, whereas in 'clear air' conditions the system noise temperature will be about 150 K, in 1% WM conditions it will rise to 190 K, reducing the *G/T* by 1.0 dB, and in 0.1% WM conditions it will rise to 257 K, reducing the *G/T* by 2.3 dB with respect to the 'clear air' case. The suggestion is that 100 K is about as low as it would be sensible to take the LNA noise temperature for such a receiving station.

In some other cases, in regions where severe rainfall is expected for prolonged periods or where the angle of elevation of the receiving antenna is very small, a LNA noise temperature as low as 100 K would be rather fruitless since its 'clear air' benefit would only be realised for a small percentage of time.

There is rarely much scope for reducing the antenna-to-LNA losses in a well designed receiving station, so the only other way to improve the *G/T* is to increase the antenna gain, and, basically, this calls for increased antenna diameter. Future developments might offer some scope for improving the aperture efficiency of a receiving antenna, especially if it does not need to be used for transmitting, but already manufacturers are claiming efficiencies as high as 70%, or −1.6 dB, so clearly there is not a great deal of room for improvement.

2.5 Link budget calculations

When expressed in their decibel forms, most of the factors which contribute to the performance of a satellite link can be accounted for using a link budget calculation, which is mainly an addition-and-subtraction exercise. This is often arranged to give the overall *C/N* for the cascaded up- and down-links as the output variable, but, of course, some other parameter, such as the receiving antenna diameter can equally be made the object of the calculation, given a required overall *C/N*.

There are a few exceptions which complicate such a calculation, requiring linear, rather than logarithmic (decibel) addition. The noise components of the up- and down-link *C/N* ratios are usually considered uncorrelated, so power addition applies and for this the *C/N* contributions from the up- and down-links must separately be converted into power ratios, inverted, added, inverted again, and then returned to decibel form, giving the overall *C/N*. This is illustrated by the following equation:

$$C/N_{(\mathrm{overall})} = 10\log_{10}[\mathrm{alog}_{10}(-C/N_{(\mathrm{up})}/10) \\ + \mathrm{alog}_{10}(-C/N_{(\mathrm{down})}/10)]$$

Also the noise temperature contributions to '*T*' in a *G/T* calculation need to be added in a linear fashion (with units of kelvins) before the logarithm of the result can be used (in dBK).

By performing several link budget calculations, treating an item such as the receiving station *G/T* or the up-link EIRP as a parameter, some interesting effects are revealed which may not be obvious from a cursory inspection.

Firstly, if the receiving earth station *G/T* is made very large the noise contribution from the down-link can become much smaller than that from the up-link, and incremental changes of this *G/T* will then have little effect on the overall *C/N*. In that case the satellite link can be described as 'up-link limited' and improvements can only be made by increasing the up-link EIRP, which will have a near decibel-for-decibel effect on the overall *C/N*, regardless of the degree of backoff of the satellite's TWTA. For the case in hand this situation would demand a very large *G/T*, much larger than could be achieved with an antenna of practical dimensions, even 18 m.

Secondly, if the reverse is true, with a very small receiving station *G/T* the down-link noise contribution can be much greater than that from the up-link. In this 'down-link limited' situation changing the receiver *G/T* can have an almost decibel-for-decibel effect on the overall *C/N*. Additionally, the up-link EIRP, or up-link fading, will still affect the overall *C/N*, but this time in a way which depends on the back-off of the satellite's TWTA. If the degree of back-off is great and this amplifier is behaving linearly (see Fig. 2) then a 1 dB reduction of the up-link power will cause a 1 dB reduction in the down-link EIRP, both the component up- and down-link *C/N* ratios will be reduced by 1 dB and the overall *C/N* will be reduced by 1 dB. Alternatively, if the TWTA is operating near to saturation (giving an effect similar to AGC) only the up-link *C/N* will be reduced by 1 dB, and the overall *C/N* will change by less than 1 dB.

For the case we are considering, the result will lie somewhere between these two extremes, and the satellite's TWTA will be operated in a fairly linear region for reasons of multiple occupancy, which will be explained in the next section.

Such link budget calculations have been used in previous work to predict the likely requirements for a receiving earth station, using values of the satellite characteristics which have been revealed to the EBU by the Eutelsat organisation. The accuracy of the means of calculation has been verified by applying this to some of the earlier tests[5] which were documented extensively; the results obtained agreed to within a small margin (±1 dB, which is the probable measurement uncertainty).

Taking the antenna diameter as a parameter (for fixed values of aperture efficiency, front-end noise temperature, etc.) and giving the received *C/N* and video signal-to-noise (*S/N*) ratios as the output variables, these predictions have shown that an antenna diameter of about 10 m will be required for a receiving station located in the South of England to serve a transportable with 72 dBW EIRP capability operating in the South of England. Operation of the transportable, for instance, in Scotland will require a greater EIRP, a larger receiving antenna, or the acceptance of a less reliable link.

2.6 Multiple occupancy of the transponder

For many years the EBU has leased one pair of Eutelsat transponders to carry television traffic, and in the past these have been operated in the most straightforward manner; each transponder has carried one FM television signal. When operating with large earth stations, this allowed the maximum available EIRP of the satellite to be used for each signal since, at least in principle, the TWTA in each transponder could be driven into saturation without causing degradation to the constant-amplitude, FM signal. When operating with a transportable earth station with a limited EIRP capability, the transponder gain was not changed so the TWTA was operated with some degree of back-off.

The transponders each have a usable bandwidth of about 72 MHz and the form of FM television signal used occupies about 36 MHz, so with the growth in the broadcasters' requirements for intra-European links various proposals have been made to increase the density of traffic carried by the transponders. The original pair of transponders operated at the same radio frequencies and used orthogonal antenna polarisations. A plan was put forward within the EBU to pass two television signals through one of the transponders, sharing the bandwidth available, whilst one television signal was passed through the other. The frequencies in this plan, like those used before, were chosen to minimise the overlap of the orthogonally polarised 'channels' to ease the requirements for cross-polar discrimination in antennas. In the case of the shared transponder the signals were not to be separated from one another by individual filtering in the satellite, but only at the receiving earth stations.

Naturally, when two signals share a transponder the available output power of the satellite's TWTA must be shared between them and the available down-link EIRP for each is reduced. Furthermore the non-linear amplitude characteristic of the TWTA leads to the generation of intermodulation products (IPs), and mutual interference can be caused by this and other non-linear effects.

If the frequency separation between the two signals is made sufficiently large the IPs will fall outside the transponder bandwidth and will be rejected by the output multiplex filter in the satellite. In that case they could not cause interference, but the power in the IPs would be wasted. Alternatively, if the separation is reduced to make better use of the centre portion of the transponder's bandwidth (which has more tightly controlled amplitude and group-delay responses), there is the potential for IPs falling within the 'channels' and causing mutual interference between the two signals.

Another mechanism for mutual interference occurs when the waveforms of both RF signals reach their peak amplitudes simultaneously, the signal voltages add and the TWTA is driven harder into a more non-linear region of its characteristic, closer to saturation. The TWTA applies a phase shift to the signal it is amplifying, and the instantaneous magnitude of this depends on how hard this amplifier is driven, so with each co-phased peak the pair of signals suffers spurious phase modulation. In the case of two FM television signals, the occurrence of such events is related in some (complicated) way to their video modulating waveforms, so the result is crosstalk between the two 'channels' which is treated as spurious FM by a FM receiver. The mutual effect is known as AM/PM transfer.

The magnitudes of these, and other unwanted effects can be controlled by driving the TWTA less hard, with a greater degree of input back-off; for example 6 dB for each input signal, which results in 4.8 dB output back-off for each output signal. These figures have been drawn from Eutelsat literature and cannot be read directly from Fig. 2, which applies to the case of a single signal.

However, the non-linear shape of the amplitude characteristic in Fig. 2 can give us a general picture of what happens to the amplitudes of two signals when they share a transponder. If one signal is input to the TWTA with large amplitude, and the other is much smaller, the input back-off is determined principally by the larger signal. If this takes the TWTA into saturation (0 dB input and output back-offs) then any subsequent small change in the combined input level results in negligible change of the output back-off, or output power. Hence, the smaller signal is suppressed. With greater degrees of input back-off the effect is less dramatic, and, generally, the degree of 'small signal suppression' can be found by differentiating the amplitude characteristic with respect to input back-off.

This gives the incremental gain of the TWTA, and in Fig. 3 this is plotted with respect to the input back-off due to the combined input signal. Note that the apparent inflection in this curve as it approaches 0 dB incremental gain is not real, it is caused by the quantising of the data used to calculate points on the curve, which was provided by Eutelsat in the form of a table.

From the input back-off due to the larger signal, the output back-off for this one can still be read directly from Fig. 2 to a fair approximation, and the corresponding value of incremental gain can be found from Fig. 3. Then for the smaller signal, which in isolation might have driven the TWTA in a more linear region of its characteristic, the output back-off is the sum (in decibels) of the value read from Fig. 2 for its own degree of input back-off, and the incremental gain. In essence, the harder the TWTA is driven by the larger signal the more the smaller signal is suppressed. It should be borne in mind, however, that second order effects such as the phase of the combined input signal have been neglected in this argument (i.e. complete 'suppression' might never occur).

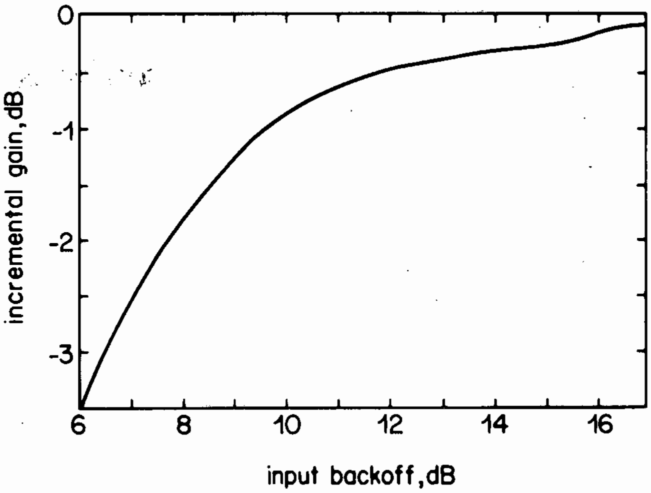

Fig. 3 - Eutelsat I-F2: Transponder 9 TWTA incremental gain variation.
Incremental gain vs. input backoff.

The practical case is often more complicated, when two signals may have similar amplitudes and a third (and perhaps others) may be present with somewhat smaller amplitude. Nevertheless the same principle applies, although the value of input back-off used might need to take into account the contributions from all three signals.

The plan for carrying three television signals in two transponders has now been superseded by one which fits two television signals, one radio signal and two narrow-band voice communication signals into each of the two transponders[6]. This became practicable some time ago when, following the failure of one transponder in the orthogonally polarised pair on board Eutelsat I-F2, another transponder was made available working at a different frequency. The requirements for cross-polar discrimination were eased and this allowed the same frequency plan to be used for both transponders, but with different centre frequencies. This plan has become the standard mode of operation, and represents the maximum density of traffic which will be carried by these transponders. Of course, there will be occasions, planned or otherwise, when a smaller number of signals will be carried.

The two transponders leased to the EBU are numbered 1 and 9, and the 'channels' in each are given unique alphabetical names. Transponder 9 is of greater interest in this context because it tends to be used more for experimental work, and this one receives up-link signals with *X*-polarisation (nominally horizontal) and down-links signals with *Y*-polarisation (nominally vertical). The plan for the centre frequencies of the important 'channels' is as follows:

Channel B

Transmit frequency = 14.440333 GHz
Receive frequency = 11.140333 GHz

Channel D

Transmit frequency = 14.475333 GHz
Receive frequency = 11.175333 GHz

Channel R

Transmit frequency = 14.493333 GHz
Receive frequency = 11.193333 GHz

The narrow-band communication channels, U and V, use very small amplitude signals and are not important in this context. Transponder 1 carries counterpart Channels A, C, Q, S and T.

Channels B and D each have a nominal bandwidth of 36 MHz, and are intended to carry FM television traffic between main earth stations in the case of Channel B, and between a transportable earth station and a main earth station in the case of Channel D. In both cases the transmitting earth station is allowed a maximum EIRP of 76.6 dBW contour-corrected (i.e. 76.6 dBW when the transmitting station is at the centre of the Eurobeam, and, with reference to the Eurobeam antenna response, correspondingly greater EIRP when it is located elsewhere). This gives the required 6 dB input back-off for each signal. The modulation characteristics of the FM signals used for such 'Eurovision' operations have been prescribed by the EBU*.

Channel R has a nominal bandwidth of 2 MHz, and is intended to carry digital, sound-only traffic between fixed or transportable earth stations, complying with the DS1 standard which has been adopted by the EBU for 'Euroradio' operations. In this case the maximum allowed earth station EIRP is 70.6 dBW contour-corrected, giving 12 dB input back-off.

The frequency plan for Transponder 9 is illustrated in Fig. 4. It is interesting to note that the centre frequencies of Channels B and D are spaced by only 35 MHz, and Channels D and R by only 18 MHz, so some degree of overlap is inevitable when the signals are fully modulated. Therefore there is a danger of Channels B and R causing Adjacent-Channel Interference (ACI) to a Channel D receiver if it is equipped with a conventional 36 MHz filter, which commonly has an equalised bandwidth of 36 MHz and a half-power bandwidth of about 39 MHz. This frequency plan was established following a series of practical tests involving several EBU members' fixed earth stations, and satisfactory levels of inter-channel interference were reported, yet one cannot help wondering whether the stations might have been equipped with alternative, narrower bandwidth receiver filters.

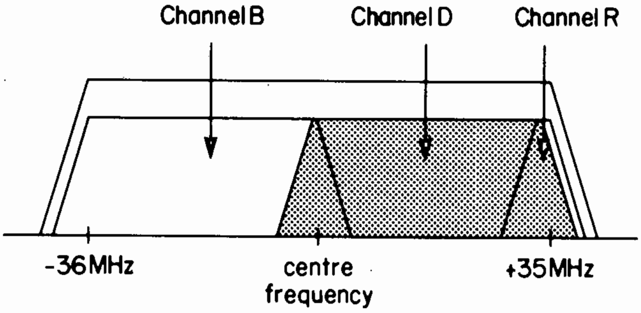

Fig. 4 - Eutelsat I-F2: Transponder 9 frequency plan (September 1989).

As a result of this, now standard, mode of operation, greater demands are placed on receiving earth stations for *G/T* since often the signals will be transmitted from the satellite at EIRPs lower than the maximum that could have been achieved with single occupancy (one signal per transponder). 'Worst case' link budget calculations must now take into account the signal suppression effects, and perhaps inter-channel interference effects as well. Whereas, with single occupancy, a 7 m receiving station might have offered adequate performance when receiving signals from a transportable with 72 dBW EIRP (and a certain set of other conditions such as the locations of the stations, weather conditions, etc.), now, with multiple occupancy, a 10 m receiving antenna is needed to maintain the same overall link performance.

2.7 Quality criteria

When judging the performance of a satellite link, some sort of quality criterion has to be applied. One that has been used in the EBU is the comparison of the signal-to-noise ratio (*S/N*) of the received signal with a target value. A value of 50 dB Unified-weighted *S/N* is considered by the EBU as the 'minimum target' value for Eurovision satellite links, applied with 99% of worst month propagation conditions.

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* Transmission using 25 MHz/V deviation with CCIR Rec. 405 pre-emphasis, and reception using a nominal 36 MHz bandwidth IF filter (having about 39 MHz noise-bandwidth in practice) and corresponding de-emphasis. The (video) baseband is low-pass filtered to 5.5 MHz.

However, at the present time FM is used exclusively on satellite television links, and FM demodulators exhibit a threshold effect, whereby at low C/N ratios the link can be impaired severely by 'threshold' noise spikes appearing in the received pictures. This is exacerbated when, as is normal EBU practice, the sound-in-syncs (SIS) system is used to carry the companion sound channel. SIS, being digital, is prone to abrupt failure when threshold noise starts to appear. For satellite links involving our transportable earth stations, operation at C/N values well above the FM threshold is not assured at all times, so for our purposes the comparison of the achieved C/N with a threshold value is a much more important quality criterion.

The difference between the achieved C/N and the threshold C/N (both in decibels) is the 'margin' against failure (in dB). If the achieved C/N is measured or calculated for 'clear air' conditions then from this failure margin one can deduce the percentage of time for which the link will probably be unavailable, with knowledge of the rainfall statistics for the earth station locations and using a suitable rainfall attenuation 'model'.

2.8 Threshold performance of FM demodulators

The actual C/N value at which threshold noise begins to appear on received pictures depends on the characteristics of the demodulator, the FM deviation used and the chrominance content of the pictures being transmitted. With standard 'Eurovision' operating conditions the threshold C/N for PAL television modulation is around 12 dB. For worst case picture material the apparent threshold is about 13 dB, and for non-critical material it may be as low as 11 dB.

When SIS is used in these conditions, errors begin to be audible (clicks and pops) at about 12.5 dB C/N. If failure of the SIS is regarded as total link failure then the threshold C/N will be about 12 dB, at which the Unified video S/N will be about 48 dB.

An example of the variation of Unified S/N with changing C/N, for a conventional demodulator, is illustrated in Fig. 5 with regions indicating the various degrees of SIS performance.

There is some expectation that these figures will be improved upon in the future when so-called 'threshold extension' demodulators become available commercially. However, at the present time, although impressive results have been reported in experimental work, there is little clear evidence that commercially manufactured versions offer a consistent 'extension' for all possible picture material and SIS.

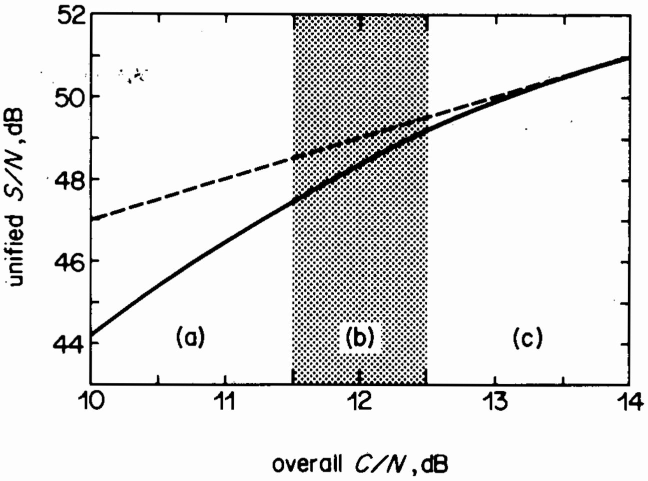

Fig. 5 - Typical variation of video S/N ratio with varying C/N ratio.

Unified video S/N ratio vs. overall C/N ratio.

——— typical curve
– – – – – hypothetical linear relationship, without a 'threshold'

(a) many SIS errors per second
(b) occasional SIS errors
(c) very few SIS errors

2.9 Previous work and the need for more tests

Theoretical link budget calculations have been performed for the case in hand, considering multiple occupancy, and from these the conclusion was that a receiving antenna of about 10 m diameter would be needed.

Practical results from the previous experiments can be used to assess the requirements for a receiving station for the specific case of single occupancy. However, the degree of extrapolation that would be needed to cover the possible cases of multiple occupancy is considered too great to be reliable. Partly as a consequence of this, and also because of the desire to check and double-check when considering such a costly project, it was necessary to verify the theoretical results by performing a further series of practical tests. The conditions of multiple occupancy were an important part of these tests. Furthermore, by using existing receiving earth stations with antennas of around 10 m diameter, it was hoped that extrapolation could be avoided.

There are other satellites which could, perhaps, be used in the future on an 'occasional use' basis, and some may offer improved link performance in such cases, especially those with 'spot beams'. However, this work is confined to the present EBU/Eutelsat I case.

Therefore, in this context the important questions to be answered were:

- What practical use can be made of a receiving station with an antenna significantly smaller than 18 m ?

. . . and if we are to proceed with a station using an antenna smaller than 18 m:

- With which of our transportables could it be used, providing a positive failure margin, and in each case what would be the value of this margin?

Only in the case of our most powerful transportable, where there is the possibility of a significant margin against failure, is the received video *S/N* of any real importance. Throughout the following text, it is worth bearing in mind that the theoretical studies indicated that a 10 m antenna would be needed.

3. DESCRIPTION OF THE TESTS AND THE TEST RESULTS

The series of tests was carried out over a period of three days, 12th to 14th September 1989. The aims were:

a) using a transportable earth station and representative fixed earth stations, with antennas of about 10 m diameter, to measure the *G/T* values achieved in practice;

b) to explore the range of up-link EIRPs that would be necessary to ensure adequate reception of signals from transportable earth stations when the Eutelasat transponder was occupied by the various combinations of several signals simultaneously.

3.1 The satellite

The tests were all carried out using Eutelsat I-F2, which is stationed at 7° East, using Transponder 9 exclusively.

In order to examine the several possible cases of multiple occupancy, a test signal was passed through Channel D whilst Channels B and R were selectively loaded and kept clear. We did not have fully 'booked' control of all three channels for the whole of the test period so some of the individual tests were performed at times dictated by the actual use of the transponder, for example, very early in the morning.

3.2 The earth stations

Receiving tests were carried out at two fixed earth stations simultaneously, a 7.6 m station in Copenhagen belonging to Danish Telecom (the PTT) and on the premises of DR (Danmarks Radio), and an 11 m station belonging to the DTI* (the UK Department of Trade and Industry) at Baldock. Apart from differences in the down-link weather conditions, the simultaneous use of two receiving stations was expected to help in cross-checking results and avoiding mistakes in the measurements. Link budget calculations have shown that an antenna size of around 10 m will meet some of the BBC requirements and this falls between the sizes of these two antennas. Of course, it is the *G/T* which really matters, not just the antenna size, but nevertheless it was hoped that the results obtained in these tests would allow the performance of a 10 m station to be predicted by interpolation.

Research Department staff participated in the taking of measurements at both Copenhagen and Baldock.

3.2.1 The up-link earth stations

The BBC's 3 m transportable earth station, UKI-1[7], shown in Fig. 6, was located at Baldock, near to the 11 m antenna, and was used to transmit test signals, including FM television signals, on Channel D. Baldock is on the −1.4 dB contour of the Eurobeam, so in principle a maximum EIRP of 78.0 dBW could be transmitted. However, for this earth station the maximum available EIRP is about 75 dBW. The DTI Baldock station does not have transmitting facilities.

The Lessive fixed earth station in Belgium was called upon to load Channel B, selectively, with a full-power (76.6 dBW contour-corrected) FM television signal or a plain carrier.

Channel R was loaded selectively with a full-power (70.6 dBW contour-corrected) DS1 radio signal using the transmitting facilities at the Copenhagen fixed earth station.

3.2.2 The down-link earth stations

The down-link signals were received by the DR 7.6 m fixed earth station at Copenhagen, shown in Fig. 7, which is on the −1.9 dB contour of the Eurobeam. The down-link signals were also received by the DTI 11 m fixed earth station at Baldock, shown in Fig. 8, which is on the −1.4 dB contour of the Eurobeam.

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* Now the Radiocommunications Agency.

Additionally, the DBP 'calibrated' earth station at Usingen (in West Germany) was called upon during some of the tests to give us figures for the EIRP of the transportable earth station and the EIRP of the satellite.

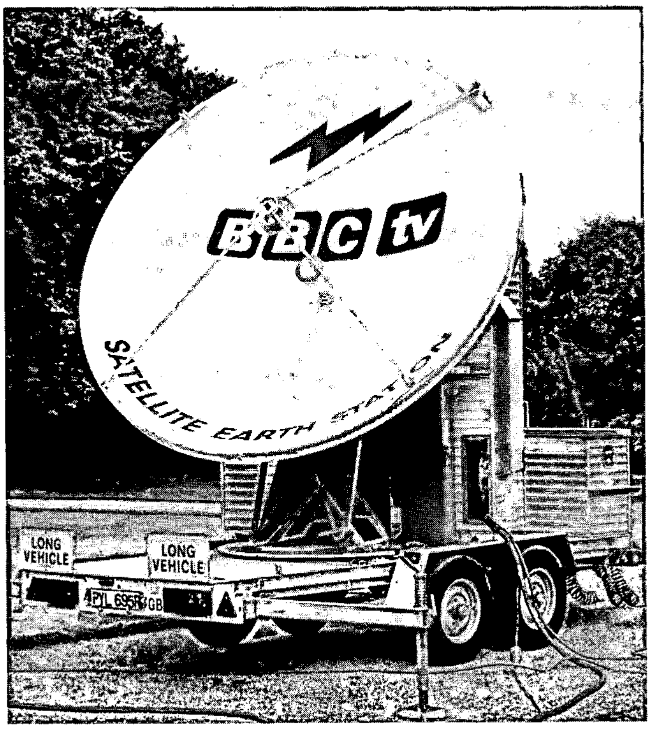

Fig. 6 - The BBC 3 m transportable earth station.

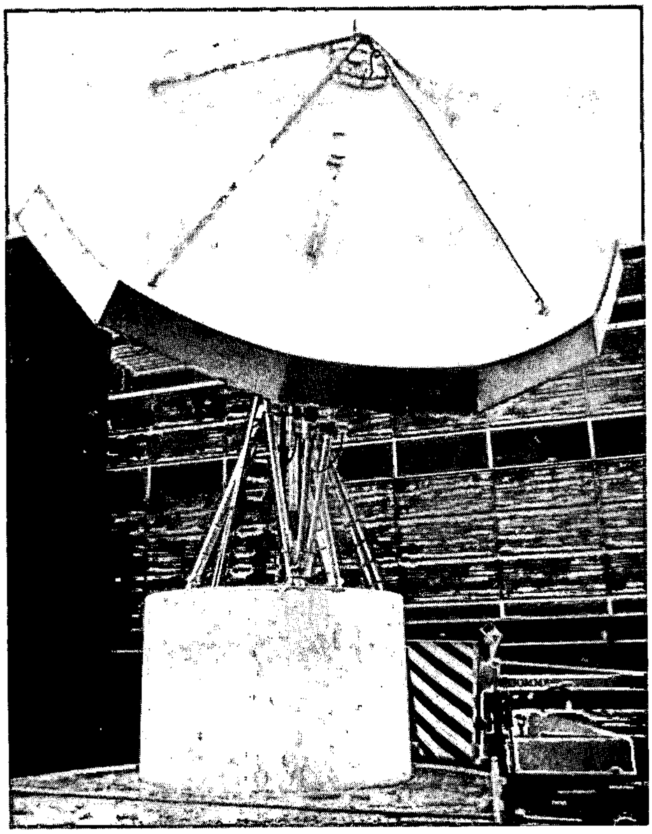

Fig. 7 - The 7.6 m earth station at Copenhagen.

3.3 Transmitting earth station EIRP measurement

In order to know what actual EIRP is being transmitted it is necessary to calibrate the transmitting earth station at one EIRP value, then a power meter coupled to the transmitting antenna feed can be used to read off different values as they are set up by altering the RF drive to the high-power amplifier (HPA).

3.3.1 Description

The only convenient way to calibrate the EIRP of our transportable was to perform a 'power balance' test, in conjunction with a second, calibrated transmitting earth station; the DBP station at Usingen. Both stations transmitted plain carrier signals at slightly different frequencies through the transponder whilst the pair of down-link signals was inspected at a receiving earth station (also Usingen in this case). Then the transmitted power at the calibrated station was varied until both down-link signals had the same magnitude. Measurement of the transmitted power and accurate knowledge of the antenna system gain at the

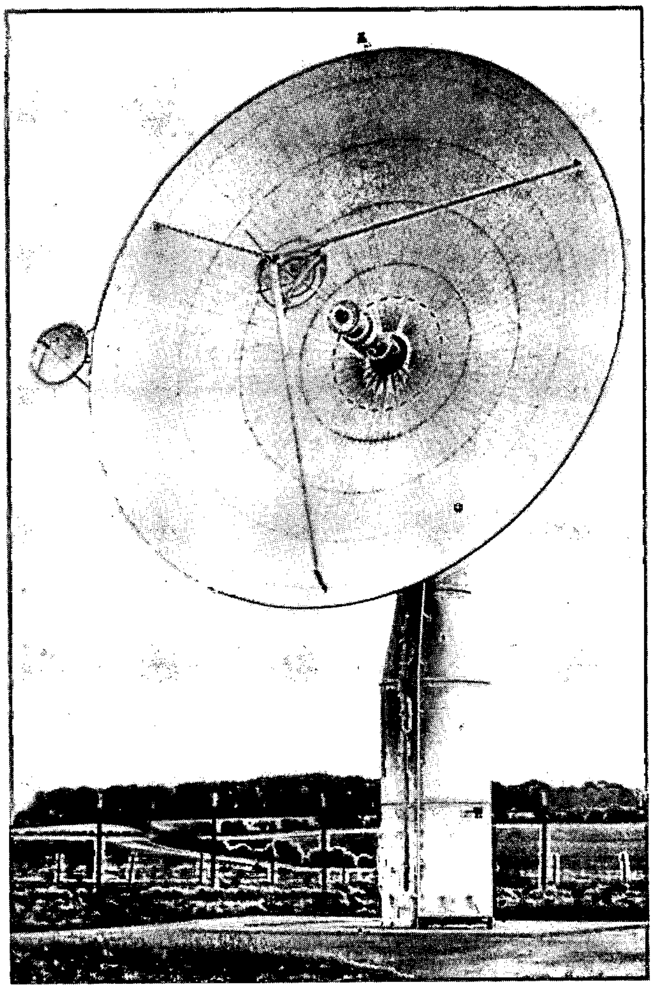

Fig. 8 - The 11 m earth station at Baldock.

up-link frequency, at the calibrated station, along with knowledge of the locations of the two transmitting stations in relation to the Eurobeam contours, revealed the EIRP of the transportable.

3.3.2 Results

First the transportable earth station was set up to radiate its maximum available EIRP, and this was measured as 74.8 dBW. Then accurate calibrations (i.e. local power meter readings) were found for the series:

74 dBW, 72 dBW, 70 dBW, and 68 dBW.

Good weather conditions prevailed during this test.

3.4 Receiving earth station *G/T* assessment

For the results of subsequent tests to be of value we needed to know the *G/T* ratios of the two receiving stations, rather than just accepting that the results apply to stations with 7.6 m and 11 m antennas. In fact it was known, at the planning stage for these tests, that the 11 m station is equipped with a wideband LNA having 3 dB noise figure (NF), or 290 K noise-temperature, whereas the present 'state of the art' for the 11 GHz band corresponds to around 1 dB NF, or 75 K noise-temperature. This implies that a possible improvement of nearly 6 dB could be made to this station in 'clear air' conditions if it was required to cover only the 11 GHz band, and to receive only FM television signals. Alternatively, it could be argued that the 'clear air' performance of this station would be similar to that of a 6 m antenna coupled to a 1 dB NF LNA. Of course, at such low front-end noise temperatures the noise contribution from the antenna can become a large component of *T* in the *G/T* as soon as rainfall starts, and the advantage of a 1 dB NF LNA over, say, a 1.8 dB device would be realised only for a small percentage of time.

The gain of the 11 m antenna at Baldock is believed to be about 62 dB, so the *G/T* in 'clear air' conditions was expected to be around 34.4 dB/K; the method of calculation is detailed in Appendix 1. For the Copenhagen station, information was received from DR that the LNA has 2.1 dB NF and the *G/T* is 32.8 dB/K.

3.4.1 Description

The method chosen for measuring the values of receiving station *G/T* was to arrange for the satellite to transmit a signal of known EIRP, and then to measure the C/N_0 (carrier-to-noise density) ratio of the signal received at the station under test. In a 'down-link limited' situation the measured value of this overall C/N_0 would be considerably smaller than the up-link C/N_0, so noise introduced by the up-link could be disregarded and the measured value could be used for the down-link C/N_0. Then, from this and the satellite's EIRP, the *G/T* of the receiver could be found with a simple calculation. In practice, using our transportable to provide the up-link signal with limited EIRP, the up-link noise was not completely insignificant and a correction was applied to account for this, using measurements of the up-link EIRP. The test method and the calculations are detailed in Appendix 2.

For measurements of the satellite's EIRP the calibrated earth station at Usingen was used again, with single occupancy of the transponder.

Because of the influences of rain attenuation on the down-link C/N_0, the only *G/T* values that could be determined easily, with confidence, were the 'clear air' values, and this required good weather conditions at receiving stations. Also, accurate measurement of the satellite's EIRP required 'clear air' conditions on the down-link to the calibrated receiving station.

The measurements were performed at one spot frequency, at the centre of Channel D.

At each earth station under test the C/N_0 was measured using a spectrum analyser connected to the 70 MHz intermediate frequency (IF) stage immediately prior to the FM demodulator.

3.4.2 Results

The complete test was performed three times over during different weather conditions, some of which, unfortunately, could not be described as 'clear air'. The series of five different values of calibrated up-link EIRP was used on each occasion, as noted in Section 3.3.2.

The results obtained at Copenhagen are plotted against the up-link EIRP in Fig. 9, where the expected 'clear air' value of 32.8 dB/K is also shown for comparison. The weather conditions which prevailed during the tests are also noted. Lines have been drawn between the data points on this figure to make the trend for each test easier to follow; no accuracy is claimed at EIRP values between the data points.

The results obtained at Baldock are plotted against the up-link EIRP in Fig. 10, where the corresponding weather conditions and the 'clear air' expected value of 34.4 dB/K are also shown.

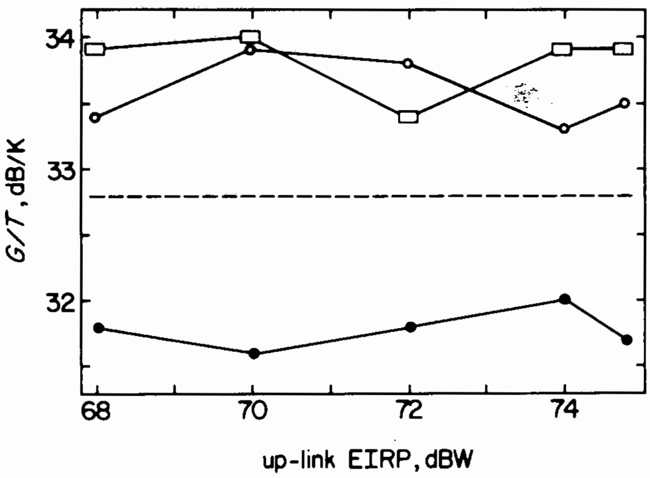

Fig. 9 - Copenhagen: results of the G/T measurements (using Channel D).

Measured G/T ratio vs. up-link EIRP.

- - - - - expected 'clear air' value
○——○ and □——□ recorded with 'clear' air conditions at receiving station
●——● recorded during heavy rainfall at the receiving station

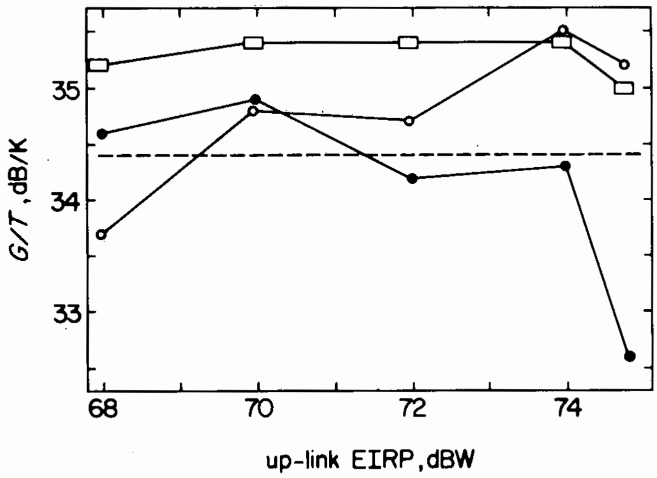

Fig. 10 - Baldock: results of the G/T measurements (using Channel D)

Measured G/T ratio vs. up-link EIRP.

- - - - - expected 'clear air' value
○——○ and □——□ recorded with fog and light rainfall at receiving station
●——● recorded with 'clear air' conditions at receiving station

3.5 Single occupancy transmission test (Channel D only)

This was the first of the series of tests aimed at assessing the absolute performance of the two receiving earth stations when receiving signals from the transportable. In this case our test signal was the only one occupying the transponder. This is the most favourable condition, and in practice this could only be assured by 'booking' all three channels for the period of transmission.

Over the range of calibrated up-link EIRPs (68 dBW to 74.8 dBW) the received C/N_0 and the video S/N were measured and the picture quality was assessed subjectively, looking particularly for evidence of threshold noise spikes. SIS was applied and the decoded audio signal was examined for evidence of digital errors (audible clicks and pops).

It was not thought absolutely necessary to wait for 'clear air' conditions before starting this, or the subsequent transmission tests because the C/N_0 of the received signal was to be measured for each value of up-link EIRP. If a small degree of rain attenuation had occurred then its value could be deduced later by comparison with the 'clear air' C/N_0 results obtained in Section 3.4.2. However, the accuracy of such a deduction would be impaired by heavy rainfall at either of the receiving stations, and this would also reduce the range of C/N_0 values for which useful results were obtained.

3.5.1 Description

At the transportable earth station the transmitted signal was derived from an FM modulator; the FM parameters were those noted in Section 2.6. Selectable video sources were provided for the 'colour pulse-and-bar' and 'EBU 75% colour bar' waveforms, and conventional SIS was applied with a 1 kHz tone fed to the audio input of the coder.

At each of the receiving stations, in addition to a spectrum analyser for measuring the received C/N_0, as described in Section 3.4.1, the IF signal was fed to a conventional FM demodulator (identical demodulators were used at the two earth stations). Elsewhere in the receiver this IF signal would have been band-pass filtered to a nominal 36 MHz bandwidth. Note that the conventional filtering for 'full transponder' operation has a bandwidth of 36 MHz over which the IF amplitude and group-delay responses are equalised. The actual noise bandwidth, which affects the C/N at which threshold effects start to become apparent, can be 39 MHz or slightly more. At Copenhagen a suitable filter was found to be built into the receiving equipment, and at Baldock a filter was used which was made at Research Department; both of these had 39 MHz noise bandwidths*.

The video output from the demodulator was fed to a picture monitor, a SIS decoder and a S/N meter.

After checking that Channels B and R were vacant, a plain carrier was transmitted at maximum EIRP (74.8 dBW) on Channel D and at each of the receiving stations the received C/N_0 ratio was measured. Television modulation was then applied and measurements were made of the Unified-weighted video *S/N*.

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* For the type of filter used, the noise bandwidth is very close to the half-power bandwidth.

The subjective quality of the received pictures was then assessed using the pulse-and-bar and colour bar waveforms, looking particularly for threshold noise. The audio output from the SIS decoder was also assessed, both with and without the 1 kHz tone, listening particularly for SIS errors appearing as audible clicks and pops. An *ad-hoc*, but fairly thorough, method was used for recording these subjective assessments using four levels for quantifying the degree of threshold noise on pictures, and four levels for quantifying the number of SIS errors per second.

This test procedure was then repeated for each of the series of five calibrated values of EIRP used before, taking measurements simultaneously at both receiving earth stations. The C/N_0 values were then converted to *C/N* by applying the known noise bandwidth.

3.5.2 Results

The complete test was performed three times over with various weather conditions prevailing at the two earth station sites.

The results obtained at Copenhagen are plotted against the up-link EIRP in Fig. 11(a) and (b), with a key showing the weather conditions that prevailed. In each case the expected trend is also plotted for comparison (assuming 'clear air' conditions). This was calculated using a link budget, but note that for the case of the *S/N* no attempt has been made to simulate the non-linear behaviour of the FM demodulator working near or below the threshold *C/N*. Therefore the expected trend of *S/N* is optimistic for *C/N* values less than about 12 dB (i.e. EIRP values less than about 73 dBW in this case).

On each of these figures a vertical dotted line is drawn at the EIRP below which the SIS was deemed to have failed completely, that is, when it was subject to many errors per second, with no seconds free from errors. At this value of EIRP the television pictures were degraded by threshold noise, but may still have been considered usable, so hereafter SIS failure was considered as link failure.

Since time permitted during the test period, a brief diversion was made to try out an alternative FM demodulator. The equipment installed at Copenhagen included PLL demodulators, and one of these was substituted for the conventional (Cowan type) demodulator. The results obtained are also shown in Fig. 11(a) and (b), with additional, smaller vertical dotted lines.

The results obtained at Baldock are plotted against the up-link EIRP in Fig. 12(a) and (b), with a key showing the weather conditions. In each case the 'clear air' expected trend is also plotted, and the SIS failure point is noted as before.

3.6 Dual occupancy transmission test (Channels B and D)

This test was essentially the same as that described in Section 3.5, with the exception that in this case our test signal and one other occupied the transponder simultaneously. The other signal, in Channel B, simulated the conditions of normal EBU television traffic being transmitted at the maximum allowed EIRP of 76.6 dBW contour-corrected, with television modulation, from the Lessive earth station.

This is a less favourable condition than the single occupancy case because the other signal was expected to cause smaller-signal suppression to our signal, and perhaps other interference effects. This condition could occur often in practice, on occasions when Channel R is vacant.

The only additional aspect that was looked out for in this case was clear evidence of interference from Channel B.

3.6.1 Description

This test was carried out in exactly the same way as for the case of single occupancy, described in Section 3.5.1.

3.6.2 Results

The complete test was performed twice with various weather conditions prevailing at the two earth station sites. A third test was not considered worthwhile because significant adjacent-channel interference (ACI) effects were apparent from Channel B at all values of up-link EIRP, and these appeared to be caused mainly by the frequency spacing of the two channels being too small for the 39 MHz actual bandwidths of the IF filters used. The presence of an interfering signal in the receiver bandwidth would make it very difficult, on analysis, to isolate the desired information about suppression effects.

It was possible to shift the tuned frequency of each of the receivers, and this was found to reduce the impact of the interference somewhat. However, a large frequency shift would represent an artificial condition

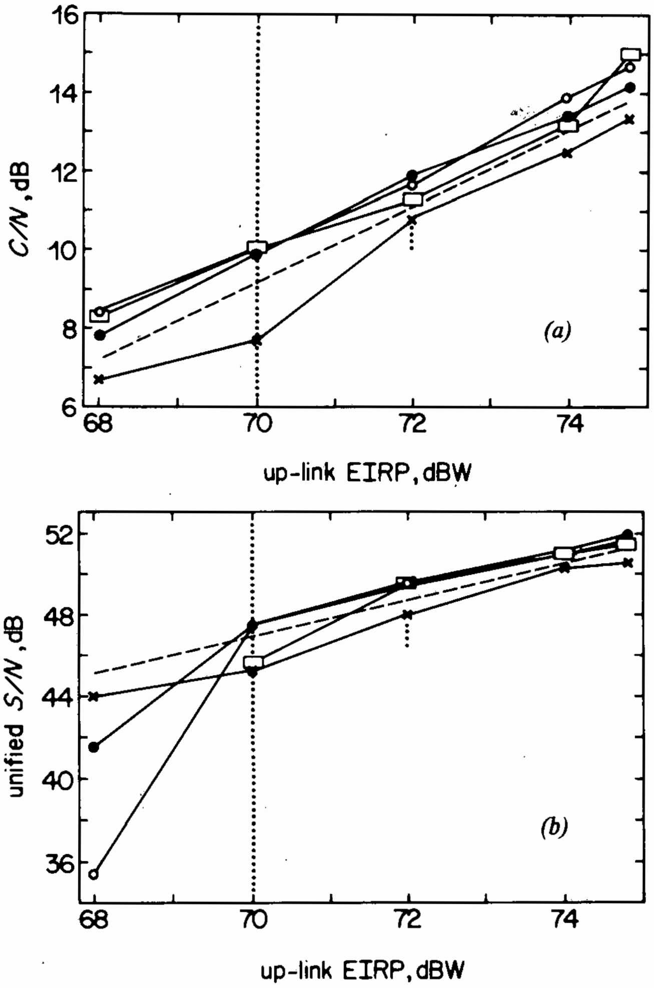

Fig. 11 - Copenhagen: results of single occupancy tests (Channel D only)

(a) Received C/N ratio versus up-link EIRP

(b) Unified S/N ratio vs. up-link EIRP

- - - - - - expected 'clear air' values

⋮ EIRP below which SIS was subject to many errors per second

o——o and □——□ recorded with 'clear air' conditions at receiving station

●——● and ×——× recorded during continuous rainfall at receiving station

conventional demodulator used for o——o, □——□ and ●——●

×——× recorded using PLL demodulator

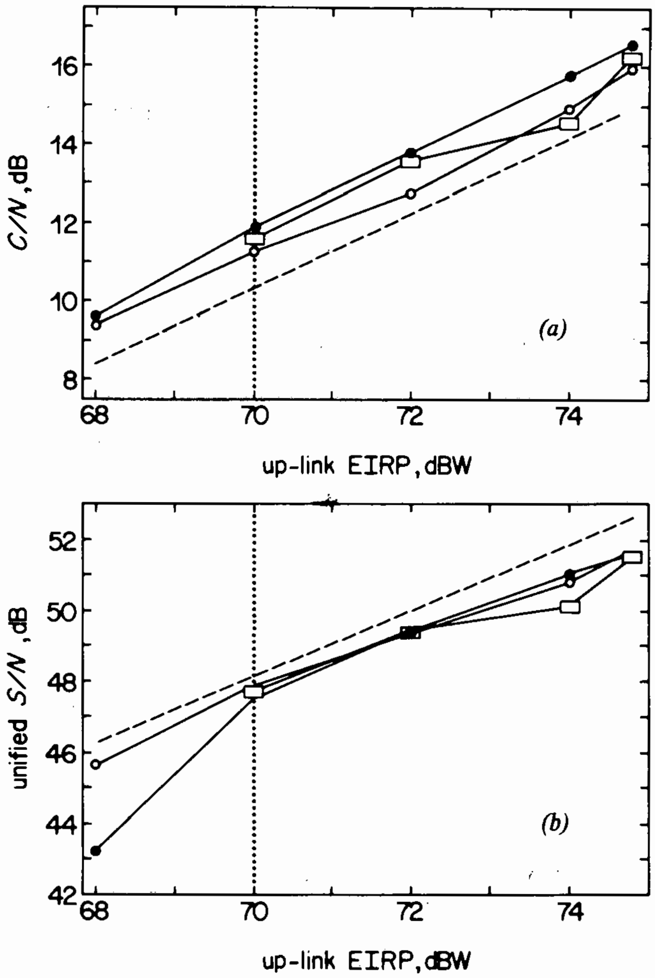

Fig. 12 - Baldock: results of single occupancy tests (Channel D only).

(a) Received C/N ratio vs. up-link EIRP

(b) Unified S/N ratio vs. up-link EIRP

- - - - - - expected 'clear air' values

⋮ EIRP below which SIS was subject to many errors per second

o——o and □——□ recorded with fog and light rainfall at receiving station

●——● recorded with 'clear air' conditions at receiving station

since in normal operation the presence of Channel R on the other side (in frequency terms) would inhibit the movement of Channel D for the same reason of ACI. Therefore only a small frequency shift was used, moving the receivers 1 MHz further away from Channel B.

The centre frequency of the up-link signal was not changed as this would have implied a departure from the EBU frequency plan that was in operation at the time. It was realised that shifting only the receivers could exacerbate the incidence of truncation noise (threshold noise which occurs when the frequency of the FM signal falls outside the receiver bandwidth), but with the test signals in use a 1 MHz shift caused less degradation to the received pictures than the ACI.

The results obtained at Copenhagen are plotted against the up-link EIRP in Fig. 13(a) and (b), with a key showing the weather conditions. In each case the 'clear air' expected trend is also plotted, and the SIS failure point is noted as before. The corresponding results for Baldock are plotted in Fig. 14(a) and (b).

3.7 Dual occupancy transmission test (Channels D and R)

This test was essentially the same as that described in Section 3.6, but Channel R was loaded

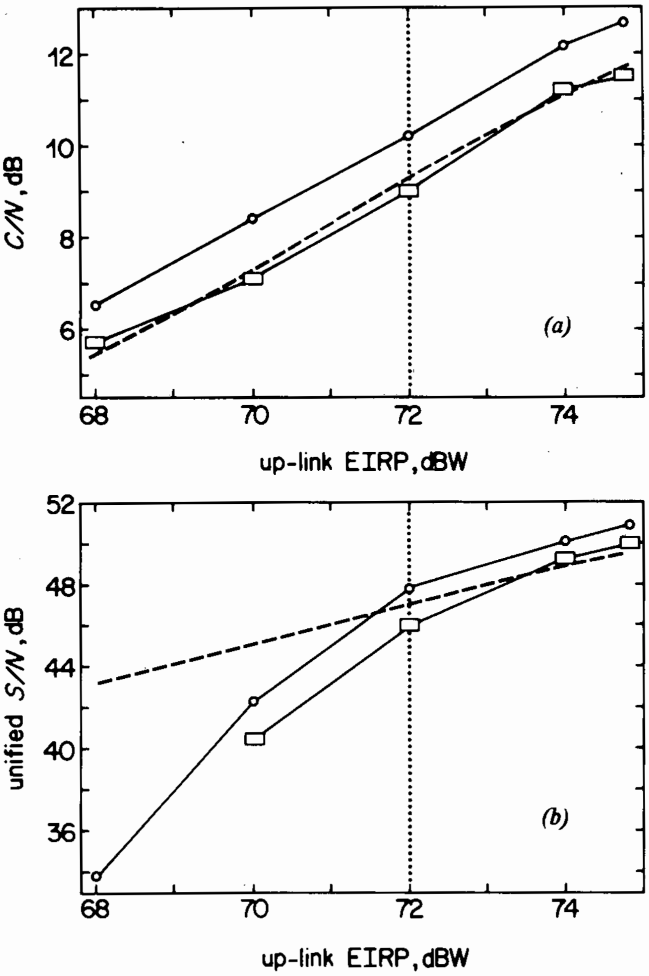

Fig. 13 - Copenhagen: results of dual occupancy tests (Channels B and D)

(a) Received C/N ratio vs. up-link EIRP
(b) Unified S/N ratio vs. up-link EIRP

-----	expected 'clear air' values
⋮	EIRP below which SIS was subject to many errors per second
○—○	recorded with 'clear air' conditions at receiving station
□—□	recorded during continuous rainfall at receiving station

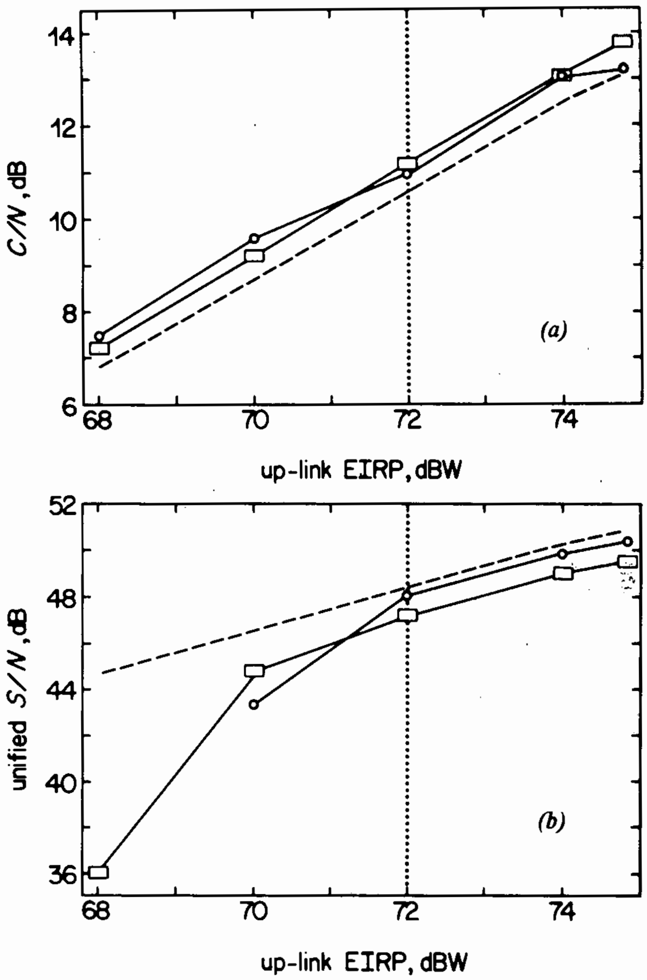

Fig. 14 - Baldock: results of dual occupancy tests (Channels B and D).

(a) Received C/N ratio vs. up-link EIRP
(b) Unified S/N ratio vs. up-link EIRP

-----	expected 'clear air' values
⋮	EIRP below which SIS was subject to many errors per second
○—○	recorded with light rainfall at receiving station
□—□	recorded with 'clear air' conditions at receiving station

instead of Channel B. The signal in Channel R simulated the conditions of normal EBU sound-radio traffic being transmitted at the maximum allowed EIRP of 70.6 dBW contour-corrected, with DS1 digital audio modulation, from the transmitting part of the Copenhagen earth station.

Again, this is a less favourable condition than single occupancy because of the small degree of suppression which would be expected to occur to our signal in Channel D. This condition could occur in practice if we had 'booked' Channel B purposely to keep it vacant, and Channel R was in use.

The additional aspect that was looked out for in this case was clear evidence of interference from Channel R.

3.7.1 Description

This test was carried out in exactly the same way as for the case of single occupancy, described in Section 3.5.1.

3.7.2 Results

This test was performed only once because severe ACI effects were apparent from Channel R at all but the largest values of up-link EIRP, and the interference appeared to be caused only by the frequency spacing of the two channels being too small for the receiver bandwidths. Therefore very little useful information could be obtained about suppression effects.

As before, shifting the tuned frequency of the

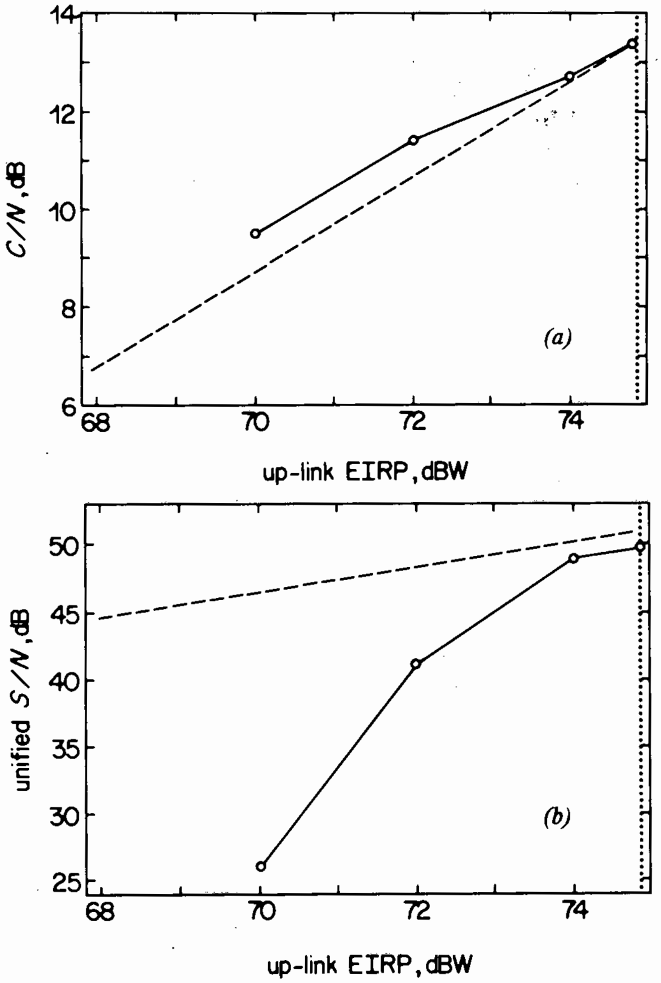

Fig. 15 - Copenhagen: results of dual occupancy tests (Channels D and R)

(a) Received C/N ratio vs. up-link EIRP
(b) Unified S/N ratio vs. up-link EIRP

- - - - - expected 'clear air' values
⋮ EIRP below which SIS was subject to many errors per second
o———o recorded with 'clear air' conditions at receiving station

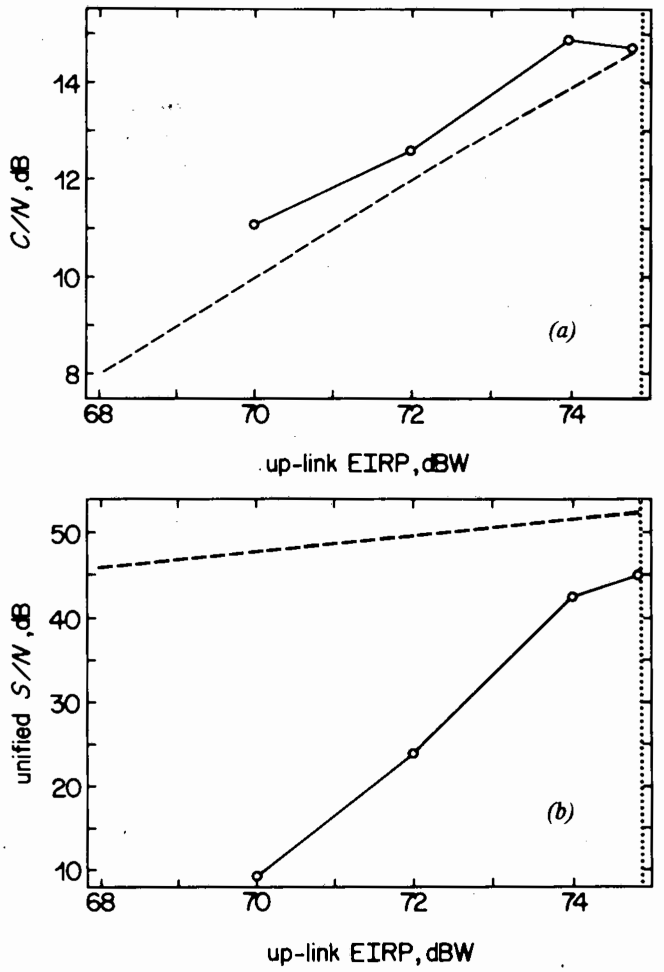

Fig. 16 - Baldock: results of dual occupancy tests (Channels D and R).

(a) Received C/N ratio vs. up-link EIRP
(b) Unified S/N ratio vs. up-link EIRP

- - - - - expected 'clear air' values
⋮ EIRP below which SIS was subject to many errors per second
o———o recorded with misty conditions at receiving station

receivers was found to help reduce the ACI effects, but their magnitude was so severe that an impractically large frequency shift would have been needed to make any significant improvement. The test was carried out once with the receivers tuned about 2.5 MHz further away from Channel R, but this was on the verge of causing severe truncation noise.

The results obtained at Copenhagen are plotted against the up-link EIRP in Fig. 15(a) and (b), with a key showing the weather conditions. In each case the 'clear air' expected trend is also plotted, and the SIS failure point is noted as before. The corresponding results for Baldock are plotted in Fig. 16(a) and (b).

3.8 Triple occupancy tests

Since the ACI problems in both dual occupancy tests could not be solved without recourse to a modified frequency plan, the planned triple occupancy tests were not carried out.

4. ANALYSIS OF THE RESULTS

The results of the tests generally show good agreement with the expected, theoretical values. The individual types of test will now be covered in detail.

4.1 Transmitting earth station EIRP

The maximum available EIRP of the 3 m transportable earth station was measured as 74.8 dBW, and this is somewhat smaller than had been expected. Similar 'power balance' tests, conducted in the past[6], have yielded figures between 75 dBW and 76 dBW, and theoretically the station should be capable of radiating up to 76 dBW. Despite investigations, no apparent fault was found with the transmitting equipment, and since there was no opportunity to repeat the test (on account of Eutelsat commitments) it was not clear whether or not a mistake might have been made at the calibrated station. A possible 0.8 dB error may have arisen in the calibration process because it is not certain that the EIRP figures were contour-corrected for the location of the calibrated earth station.

In a later series of tests, the maximum EIRP was checked again, and was found consistently to be 75.5 dBW. This figure is more credible, and this might mean that all the results presented here should be considered to apply to EIRP values about 0.7 dB greater than shown in the figures.

4.2 Receiving earth station *G/T*

It is important to establish the actual *G/T* values for the two earth stations. In view of the limited accuracy of the measurement method, from the many results obtained possibly the safest conclusions would be:

about 33 dB/K for Copenhagen,

and

about 35 dB/K for Baldock.

Note that when the expected values of *C/N* and *S/N* were calculated for plotting the dashed lines in Figs. 9 to 16, the 'clear air' *G/T* values used were those notified (or implied) by the station operators: 32.8 dB/K for Copenhagen and 34.4 dB/K for Baldock.

In the results presented, a correction has been applied for the 0.8 dB error in the values of satellite EIRP, noted in the previous section, which was definitely present in this case. Looking at Figs. 9 and 10, the implication is that the actual 'clear air' *G/T* values, for both stations, were greater than expected. This is rather unlikely, and what the results probably show is the accuracy limitation.

The consistency with changes of the up-link EIRP is generally good, and only a few of the measured values depart significantly from the expected general trend. The reduction of the *G/T* values during rainfall appears largely as would be expected.

4.3 Transmission tests

4.3.1 Channel D only

Generally, the results from these tests show that for both receiving stations threshold conditions were reached with an up-link EIRP of about 70 dBW, and Unified *S/N* values of 50 dB were obtained using about 73 dBW. On reflection, if the EIRP figures are in error, the required values of EIRP for these conditions may be 0.8 dB greater in practice.

In the single occupancy tests the 'clear air' *S/N* values measured at Copenhagen show a trend which is slightly greater than expected. However, for Baldock the recorded *S/N* values are consistently smaller than expected, and the threshold *C/N* appears to be some 2 dB greater than for Copenhagen. This is unlikely to have been caused by differences in the demodulators or the instrumentation, as items of equipment of the same type were used at the two stations and the equipment was compared, favourably to small fractions of a decibel, in the laboratory at Research Department.

It is more likely that the discrepancy between the *S/N* and *C/N* was caused by the FM demodulator at Baldock being fed with an IF signal which was not at the optimum level. The FM demodulator used contains a limiter which has been found only to work correctly over a certain range of IF input signal levels.

Whereas the demodulator at Baldock achieved the expected threshold *C/N* for SIS failure of around 12 dB (see Fig. 5), it is rather surprising that the same type of demodulator used at Copenhagen achieved an apparent threshold *C/N* as low as 9 or 10 dB, even when the coarse quantising of the measurements is taken into account (the 2 dB steps of EIRP variation). The only explanation that can be tendered is that the criterion established in quiet laboratory conditions for SIS failure, noted in Section 2.8, might have been more stringent than that applied in the Copenhagen earth station, where noisy TWTA fans were close at hand. Maybe all the results for Copenhagen should be viewed in the light of this, although it is not a satisfactory explanation.

The brief diversion to examine the performance of the PLL demodulator at Copenhagen is interesting because the corresponding plot of *S/N* versus up-link EIRP in Fig. 11(b) does indeed show some degree of 'threshold extension' (i.e. there is no apparent 'knee' in the plot). The actual values of *S/N* were smaller than for the conventional demodulator, but Fig. 8(a) shows that the *C/N* values recorded during this test were correspondingly smaller, because of rainfall attenuation.

However, this demodulator exhibited a relatively poor performance with SIS, and the threshold *C/N* for SIS failure was about 1 dB greater in this case than for the conventional demodulator. Also it was found that this demodulator was easily upset by over-deviation, producing truncation noise effects when the conventional demodulator was still able to output a clean video signal.

An earlier test involving the Copenhagen station and our 3 m transportable had yielded some anomalous results, showing SIS failure at a surprisingly large up-link EIRP. Maybe significant improvements could have been obtained on that occasion by reducing the FM deviation of our up-link signal.

4.3.2 Channels B and D

Again the *S/N* values measured at Copenhagen, at high levels of up-link EIRP, are larger than expected whilst those measured at Baldock are smaller. The reason is possibly the same as noted in the previous section.

The outcome of these tests is that some 2 dB increase in up-link EIRP (i.e. 72 dBW) was needed to maintain 'at threshold' conditions, at both stations, when Channel B was loaded as well as our Channel D. Unified *S/N* values of 50 dB were only just reached with the maximum EIRP. However, as noted earlier, some of the degradation in this case must be attributed to the strong ACI, which would not be present if the transponder frequency plan was revised using a frequency spacing more appropriate to the receiver bandwidths. Alternatively, the receiver filters could be specified by the EBU to have, say, 30 MHz (nominal) bandwidth instead of the 36 MHz specified presently, with a corresponding reduction in the FM deviation used, but, of course, this would reduce the maximum *S/N* achievable.

4.3.3 Channels D and R

The results for this case of dual occupancy echo the comments of the previous section. At both receiving earth stations the ACI was so severe that the SIS was unusable at all values of EIRP used, even when the measured *C/N* was well above the expected 11 dB threshold. The vertical dotted lines indicating the SIS failure points on Figs. 15 and 16 have been drawn (artificially) at an EIRP greater than 74.8 dBW simply to illustrate this point.

It should be noted that although Unified *S/N* values apparently as low as 9.3 dB were measured and have been plotted, in these circumstances the video signal was completely unusable.

5. DISCUSSION OF THE RESULTS

Firstly the following general points can be observed from the results of these tests:

(1a) The theoretical predictions of the performance of these satellite links have been shown to be reasonably accurate.

(1b) Assumptions made during the process of link-budget calculation appear to be valid. An example is the relationship between the *S/N* and *C/N* of received signals, which is affected by AM/PM conversion in the satellite's TWTA. Detailed information about the magnitude of this effect is rarely available from satellite operators such as Eutelsat.

(1c) Some apparent inadequacies of the present EBU multiple occupancy arrangement have been demonstrated, and consequently the EIRP requirements for dual occupancy with Channel R, and triple occupancy, were not found.

Secondly, regarding the receiving earth stations it was observed that:

(2a) The average measured values of 'clear air' *G/T*, for the down-link frequency used, were at least as great as the expected values.

(2b) At Baldock, the FM demodulator was not working as well as expected, but at Copenhagen the demodulator exceeded expectations. The reasons for these anomalies have not been found. The result was that both stations achieved very similar performance in terms of *S/N* versus up-link EIRP and the EIRP required for threshold conditions, despite the difference between their measured *G/T* ratios and the corresponding difference between the measured *C/N* ratios.

Because the two stations provided similar performance, a number of conclusions can be drawn from the results, which are common to both and applicable to any other station achieving similar threshold performance. These conclusions are specific to the particular transponder that was used:

(3a) With single occupancy conditions, such stations could provide usable television and SIS signals from a transportable earth station operating in the South of England during clear weather with an EIRP of at least 70 dBW. At the maximum available EIRP of the 3 m transportable earth station (measured as 74.8 dBW, but believed to be slightly greater), the margin against SIS failure was about 5 dB, in terms of either overall *C/N* or up-link EIRP. The margin required to cater for 1% worst month down-link fading is about 1.1 dB so, in operational use, a minimum up-link EIRP of 71.1 dBW would be needed to provide protection against 1% worst month rainfall.

(3b) With Channel B active as well as Channel D, and with steps taken to reduce the ACI introduced by the present frequency plan, such stations could provide usable signals for the same conditions as in (3a) above, in clear weather for an EIRP of at least 72 dBW, or 73.1 dBW to achieve a similar fading margin.

A few riders follow if it is accepted that multiple occupancy will continue to be employed, and assumed that steps are taken to solve the ACI problem without prejudice to the performance of Channel D:

(4a) Such stations would be of general use with only one of the existing BBC transportable earth stations when it was operated in Great Britain; the 3 m station capable of (at least) 74.8 dBW EIRP.

(4b) With the same premises, such stations could only operate reliably with a 72 dBW transportable during 'clear air' conditions, or if Channel B had been 'booked' as well as Channel D, purposely to keep it vacant.

(4c) The transponder used is known to provide a beam-centre, saturated down-link EIRP of 41.5 dBW and this has been used in the calculation of expected *C/N* and *S/N* values, but Eutelsat guarantees only 39 dBW. If this minimum was ever applied, due to aging of the TWTA or following the move to another transponder, it would reduce the overall *C/N* and *S/N* values by some 2 dB. Then, with dual occupancy, such receiving stations would be unusable with a 72 dBW transportable and would provide only a scant fading margin for the 3 m transportable.

As mentioned in the Introduction, to fulfil the primary aim of serving a 72 dBW transportable operating in the South of England, and to provide an adequate fading margin during conditions of dual occupancy would require a *G/T* of about 36 dB/K for a receiving earth station also located in the South of England. This implies a receiver performance some 3.5 dB better than the Copenhagen station (including the 0.5 dB difference in the Eurobeam radiation pattern between Copenhagen and the South of England).

Assuming that the eventual use of triple occupancy will cause about 0.5 dB further degradation, relative to Channel B and D dual occupancy, and that SIS failure would normally correspond to a threshold *C/N* of at least 11 dB (i.e. up to 2 dB greater than the apparent threshold *C/N* recorded at Copenhagen), this *G/T* would then provide a fading margin of the order of 1 dB, which would be adequate providing that it was not achieved only by using a very low noise front-end. Of course, operation of the transportable at locations further out from the centre of the Eurobeam (for instance in Scotland) will reduce this margin (by about 1 dB in this instance), but in some cases it might be considered acceptable to operate with little or no margin because of the potential benefits of a satellite link.

A table of link-budget results is presented in Appendix 3, considering triple occupancy and an up-link EIRP of 71.8 dBW (i.e. what can be expected practically from a 72 dBW transportable when it is being used operationally, not in a controlled test). This should make it clear that the minimum *G/T* requirement is indeed 36 dB/K, or slightly greater. However, to show all the possible variations on this theme, such as different locations of the up-link station, in one table would be impractical.

A *G/T* of 36 dB/K requires an antenna diameter of the order of 10 m, with an LNA noise temperature of 150 K or less. Commercial systems which will meet this requirement are understood to be available.

6. RECOMMENDATION

These tests appear to have revealed some inadequacies in the present arrangement adopted by the EBU for multiple occupancy of the two transponders leased on Eutelsat I-F2.

The present frequency plan for Transponder 9 uses a spacing of 35 MHz between the centre frequencies of Channels B and D, and 18 MHz between Channels D and R. On the basis of the nominal channel bandwidths specified by the EBU, of 36 MHz for Channels B and D, and 2 MHz for Channel R, there are mutual overlaps between adjacent channels, each of 1 MHz width. The types of signal involved make some use of all the restricted bandwidth available and there is no reason why a Channel D receiver should not try to respond to an interfering signal in the upper or lower 0.5 MHz extremity of its filtered bandwidth. Thus the present arrangement is a recipe for ACI. The same applies to Transponder 1 with its counterpart channels.

The recommendation is, therefore, that this arrangement should be revised and, fortunately, this appears to require little more than the change of two channel-centre frequencies.

The gain and group-delay frequency responses of the satellite transponders are each equalised to provide a usable bandwidth of about 72 MHz, and outside this band the responses are inferior. The ultimate bandwidth approaches the frequency spacing of the transponder centre frequencies which is 80 MHz. These frequency responses are due mainly to the filtering characteristics of the input- and output-multiplex filters, between which the TWTAs are connected in the satellite. The present plan uses the full 72 MHz and if the inter-channel spacing was increased then inferior frequency responses would have to be accepted for either, or both of the outer channels (B and R). It would have to be established, perhaps by experiment, whether such responses would impair the traffic carried in these channels.

Since these tests were carried out, a further series of tests has revealed that the PSK 'Euroradio' signal is remarkably rugged when passed through a channel with uneven frequency responses, and at the time of writing a new proposal from the BBC is being considered by the EBU, to shift Channels Q and R up by 2.5 MHz into the non-equalised regions at the edges of the transponder bandwidths. It has also been proposed that Channels A and B should be shifted down by 1 MHz. If accepted, these changes should allow the three main channels to share each transponder without overlap of their nominal bandwidths, and with the television channels kept largely within the equalised 72 MHz portion. This will certainly reduce the incidence of ACI.

7. CONCLUSIONS

A series of practical tests has been carried out using two earth stations with antennas of around 10 m diameter to receive signals from a BBC transportable transmitting earth station, relayed by one of the EBU-leased transponders on Eutelsat I-F2. These tests have established the level of performance we can expect to achieve when, in the future, a receiving earth station is built near to, or within BBC premises in London, using an antenna of similar size.

In comparison with the present arrangement, for which we use the BTI 18 m earth station at Madley, the use of a smaller receiving antenna will inevitably reduce the number of options for which of the BBC transportable earth stations can be used 'in the field'. With multiple occupancy of the transponder, and an up-link from anywhere in Great Britain, a 10 m antenna will serve transportables which can achieve 72 dBW EIRP, of which there are presently two in use in the BBC. A smaller antenna, for instance 7 m, would limit the choice to one; the most powerful, achieving about 75 dBW. A 10 m station could provide a fading margin of about 1 dB for a 72 dBW up-link EIRP, when the transportable was operated in the South of England, and about 4 dB for 75 dBW EIRP (considering failure at 11 dB *C/N*). However, a 7 m station would provide about 1 dB margin in the latter case and a negative margin for 72 dBW EIRP; the link would be potentially unreliable, even in clear weather.

8. FURTHER WORK

The results presented in this Report are specific to the use of the Eutelsat I-F2 satellite, and transponders which have Eurobeam down-links. There will be differences whenever other Eurobeam transponders on this or other Eutelsat I satellites are used. The differences occur because these transponders achieve actual performances which are better, to various degrees, than their minimum requirements. These differences are small, amounting to overall *C/N* variations of the order of 1 dB from one transponder to another, but in our situation, where minimal margins are available, these can be significant.

Around the end of 1989 a number of unforeseen changes of transponders were imposed by Eutelsat, owing to the shortage of station-keeping fuel on a satellite which served small, non-tracking earth stations. These changes have an impact on the *G/T* requirement for a receiving station and in some cases the differences in performance will lead to different conclusions from those reached in this text. Therefore, especially in the cases of the transmission tests, a comparative study will need to be made before a final decision is taken about the required minimum *G/T* (i.e. the antenna diameter). However, the information contained in this Report should form a good basis for placing reliance on predicted performance, calculated in a similar manner to that given.

In 1992, the EBU leases are expected to be transferred to Eutelsat II-F4, which should have significantly improved characteristics relative to the series I satellites. This change has been foreseen and, so far, has not affected our plans for operation with a series I satellite over the next two years.

9. ACKNOWLEDGEMENTS

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APPENDIX 1

Calculation of the *G/T* Ratio of a Receiving Earth Station

The *G/T* ratio, or 'figure of merit' of a receiving earth station, expressed in units of dB/K, can be calculated using the following equation:

$$G/T = G - T - A - B \quad \text{(dB/K)}$$

where:

G is the antenna gain expressed in dBi (relative to the gain of an isotropic antenna).

T is the receiving system noise temperature expressed in dBK(relative to 1 kelvin temperature). This has several components which will be listed later.

A is the total of dissipative coupling losses between the antenna and the LNA, expressed as a positive value in dB. Such losses are introduced by lengths of waveguide and waveguide switches, etc.; components essential to the normal operation of an earth station.

B is the total of non-dissipative losses expressed as a positive value in dB. Non-dissipative losses are introduced by mis-pointing of the antenna and polarisation mismatches. For a properly aligned earth station antenna with tracking, B should be extremely small.

The system noise temperature, T can be calculated using the following equation:

$$T = 10\log_{10}[\alpha T_A + (1 - \alpha)T_0 + (F - 1)T_0] \quad \text{(dBK)}$$

where:

α is the feed system loss expressed as a power ratio, so:

$$A = 10\log_{10}(\alpha)$$

T_A is the effective noise temperature of the antenna in kelvins, which itself contains several components. Those arising from the main beam of the antenna's response are caused by the 'cold sky' background radiation, by 'warm' atmospheric gases, and by 'warm' rainfall. Those arising from other, sidelobe responses are caused by the 'warm' atmosphere and the 'warm' ground. There might also be a small component caused by losses inherent to the antenna structure (e.g. the surface resistance of a dish reflector).

In this context 'warm' means around 290 K, the conventional reference temperature for noise measurements. T_A is not easily measured, but is sometimes quoted by antenna manufacturers for their products. It is probably assessed by integrating portions of the antenna's radiation pattern in relation to laminar regions of ground, atmosphere and 'cold' sky. The proportion of this noise which reaches the LNA via the feed system loss is accounted for by the component αT_A.

Since T_A is dependent on rainfall, the *G/T* should really be considered as a statistical variable. However, the value that is usually quoted is the 'clear air' value, which applies when there is no rainfall in the down-link path from the satellite.

T_0 is the reference temperature, 290 K, and, on the assumption that the feed system has this physical temperature, the noise introduced by losses in the 'warm' feed system is accounted for by the component $(1 - \alpha)T_0$.

F is the overall Noise Factor of the active devices in the receiving system, expressed as a ratio, referred to the input port of the LNA. This is generally not quite as good (i.e. as low) as the Noise Factor of the LNA itself because of unwanted local-oscillator phase-noise (which affects FM receivers), although the noise contribution of amplifying stages downstream of the LNA should be insignificant; this relies on having a large gain in the LNA.

Noise Factor is related to the more common Noise Figure, N, by:

$$N = 10\log_{10}(F)$$

and

$$F = 1 + T_{EQ} / T_0$$

where T_{EQ} is the equivalent noise temperature of the active devices in the receiving system, referred to the input port of the LNA. In the equation for T, the component $(F-1)T_0$ represents T_{EQ}

Taking, for example, the Baldock station working at 10.975 GHz, the figures we have been given are $G = 60$ dBi, $A = 0.2$ dB and $N = 3$ dB. B would be expected to be very small, perhaps 0.2 dB at worst, and it then remains for T to be assessed.

From the given value of N, $F = 2.0$, so $(F-1)T_0 = 290$ K, and from the given value for A, $\alpha = 0.955$, so $(1-\alpha)T_0 = 13$ K.

Taking the 'cold sky' background as 3 K, the gaseous attenuation in the atmosphere as 0.1 dB (an average value for the path between Eutelsat I-F2 and Great Britain at this frequency), rainfall as zero, the noise temperature of the atmosphere and ground as 290 K (an approximation), and assuming that 5% of the total power received by the antenna arises from the ground via wide-angle sidelobes (an assumption), we get an effective antenna noise temperature of $T_A = 30$ K, so $\alpha T_A = 29$ K.

In total $T = 10\log_{10}(332) = 25.2$ dBK, so the 'clear air' $G/T = 34.4$ dB/K.

APPENDIX 2

Assessment of the G/T Ratio of a Receiving Station by Simple Measurements

The method chosen for assessing the G/T ratio of the receiving earth stations may not be the most accurate, but it was considered more practicable than some of the 'classical' methods which use radio-stars with known emissivities, especially in view of the limited ranges of azimuth motion which were available for the two stations under test. It relies on our ability to obtain from Eutelsat accurate measurements of the satellite's EIRP, whilst at the earth station under test simple C/N_0 measurements are taken. Of course, the accuracy of the result depends on weather conditions and there really is no substitute for 'clear air' conditions. Also, for accuracy and to keep the necessary calculations fairly simple, single occupancy of the transponder is required.

A CW test signal is transmitted from the transportable earth station to the satellite, with a known up-link EIRP, and the down-link EIRP of the satellite is found by Power-Flux Density (PFD) measurement at a calibrated receiving station (Usingen). Then, at each station under test the received, overall C/N_0 is measured. The overall C/N_0 contains noise components from both the up- and down-links, and the values of these can be calculated from separate link budgets for the up-link, and for the down-link with the unknown receiver G/T as a parameter. Combining these results gives the G/T.

Rather than rely on a single test for each receiving station, at one EIRP, by varying the up-link EIRP over a range a number of results can be obtained which should, ideally, be identical. If a systematic variation is found this is likely to be caused by a non-linear effect in the receiving station or in the measuring equipment, and this should be rectified before repeating the test.

Up-link Budget

The link budget for the up-link from the transportable earth station to the satellite is as follows, expressing all quantities in decibel form:

	Transportable earth station EIRP	$E_{(up)}$	dBW
−	up-link isotropic loss	$L_{(up)}$	dB
−	up-link atmospheric attenuation	$A_{(up)}$	dB
−	up-link beam contour	$C_{(up)}$	dB
+	satellite transponder beam-centre G/T	G_s	dB/K
−	Boltzmann constant	k	dBW/Hz/K
=	up-link C/N_0	$C/N_{0(up)}$	dBHz

... assuming 'clear air' conditions and that the antenna on the transportable earth station has not moved since the up-link EIRP was last calibrated.

In other words:

$$C/N_0 = E_{(up)} - L_{(up)} - A_{(up)} - C_{(up)} + G_s - k$$

where:

$E_{(up)}$ is a figure in the range 68 dBW to 75 dBW, the useful range of EIRPs available from the 3 m transportable earth station.

$L_{(up)}$ is 207.3 dB, the loss due to spherical spreading at 14.27 GHz between two hypothetical isotropic antennas spaced 38600 km apart, that being the length of the up-link path between Baldock and the satellite at 7° East.

$A_{(up)}$ is 0.2 dB; an average value for this up-link path at 14.27 GHz. Note that no allowance has been made for rainfall attenuation, simply because we cannot measure it; this test must be carried out in 'clear air' conditions.

$C_{(up)}$ is 1.4 dB for Baldock.

G_s is 1.5 dB/K. This is the present value for the satellite's *G/T*, according to information released by Eutelsat.

k is −228.6 dBW/Hz/K. The Boltzmann constant is the link between the noise temperature of the satellite's receiver (as contained in *G*) and the noise power component of the up-link C/N_0.

Inserting values for the constants, we get:

$$C/N_0 = E_{(up)} + 21.2 \quad \text{(dBHz)}$$

Also, the operating point of the satellite TWTA can be assessed by calculating the effective Incident Power-Flux Density (IPFD) at the satellite (i.e. the equivalent PFD arriving at the satellite's up-link receiving antenna from its beam-centre direction), and then the degree of input back-off.

Thus:

	Transportable earth station EIRP	$E_{(up)}$	dBW
−	up-link spreading loss	S	dBm^2
−	up-link atmospheric attenuation	$A_{(up)}$	dB
−	up-link beam contour	$C_{(up)}$	dB
=	effective IPFD	P	dBW/m^2

and:

	beam-centre IPFD for saturation	I	dBW/m^2
−	effective IPFD	P	dBW/m^2
=	input back-off	B	dB

with the same assumptions as before.

Therefore:

$$B = I - E_{(up)} + S + A_{(up)} + C_{(up)}$$

where:

S is 162.7 dBm^2, the link between the EIRP of the up-link earth station and the PFD incident at the satellite for the up-link path length of 38600 km. This is not frequency dependent.

I is 80.2 dBW/m^2, according to Eutelsat documentation, for Transponder 9 at the transponder gain setting which is currently in use for EBU operations.

So:

$$B = 84.1 + E_{(up)} \quad \text{(dB)}$$

With a value for the input back-off, the incremental gain, *Q* (dB) of the satellite TWTA can be found using Fig. 3. The non-linear relationship between *Q* and *B* is not easily expressed analytically.

Noise generated in the up-link (from the earth, atmosphere and satellite receiver's front-end) contains both AM and PM components, but only the AM component is significant when the noise level is eventually measured using a spectrum analyser. On passing through the satellite TWTA the AM noise component suffers a degree of 'small signal suppression' equal to the incremental gain, so the effective up-link C/N_0 is increased by this amount. Therefore:

$$\text{effective } C/N_0 = E_{(up)} + Q + 21.2 \quad \text{(dBHz)}$$

Of course, at this stage the down-link EIRP could also be found using the figure for the input back-off with Fig. 2, but this would be subject to many potential elements of small inaccuracy. It was considered much safer to rely on measured values for the down-link EIRP.

Down-link Budget

The link budget for the down-link from the satellite to the earth station under test is as follows:

	Satellite beam-centre EIRP	$E_{(\mathrm{down})}$	dBW
−	down-link isotropic loss	$L_{(\mathrm{down})}$	dB
−	down-link atmospheric attenuation	$A_{(\mathrm{down})}$	dB
−	down-link beam contour	$C_{(\mathrm{down})}$	dB
+	earth station G/T	G/T	dB/K
−	Boltzmann constant	k	dBW/Hz/K
=	down-link C/N_0	$C/N_{0(\mathrm{down})}$	dBHz

. . . with similar assumptions about the precision of antenna pointing and 'clear air' conditions. In other words:

$$C/N_{0(\mathrm{down})} = E_{(\mathrm{down})} - L_{(\mathrm{down})} - A_{(\mathrm{down})} - C_{(\mathrm{down})} + G/T - k$$

where:

$E_{(\mathrm{down})}$ is a figure in the region of 32 dBW, depending on the up-link EIRP.

$C_{(\mathrm{down})}$ is 1.9 dB for Copenhagen and 1.4 dB for Baldock.

$L_{(\mathrm{down})}$ is 205.1 dB at 10.98 GHz for the down-link path from the satellite at 7° East to Copenhagen, where the path length is 38973 km, and 205.0 dB for the path to Baldock.

$A_{(\mathrm{down})}$ is 0.1 dB, an average value for either down-link path at 10.98 GHz, with no allowance for rainfall attenuation.

G/T Assessment

Inserting values for the constants and rearranging the order of the equation to make the *G/T* the output variable, we get:

$$G/T = C/N_{0(\mathrm{down})} - E_{(\mathrm{down})} - 21.5 \quad \text{(dB/K) for Copenhagen}$$
$$G/T = C/N_{0(\mathrm{down})} - E_{(\mathrm{down})} - 22.1 \quad \text{(dB/K) for Baldock}$$

The hypothetical down-link C/N_0 is related to the measured, overall C/N_0 and the effective up-link C/N_0 by converting from the decibel forms into inverse power ratios (i.e. noise-density/carrier ratios) and subtracting the up-link component from the overall noise.

The following equation gives the result in units of dBHz:

$$C/N_{(\mathrm{down})} = -10\log_{10}[\mathrm{alog}_{10}(-C/N_{(\mathrm{overall})}/10) - \mathrm{alog}_{10}(-C/N_{(\mathrm{up})}/10)]$$

. . . so, by calculating the up-link C/N_0, measuring the overall C/N_0, and applying the above equations with the appropriate value for the parameter which is affected by the location of the earth station, the *G/T* for each station can be found.

APPENDIX 3

The Effect of Varying the Size of the Receiving Antenna

Using a computer to calculate a typical link budget for the complete satellite link from a transportable earth station to a fixed receiving earth station, using Eutelsat I-F2, Channel D, with triple occupancy, the calculation can easily be repeated a large number of times in order to show the effect of varying the diameter of the antenna at the receiving earth station. At the same time the rainfall conditions on the up- and down-link paths can be treated as parameters. This leads to the following table, where, for each antenna size, three propagation conditions have been considered:

(a) 'clear air' conditions on both the up- and down-link paths;

(b) 1% worst month conditions on the up-link path and 'clear air' on the down-link path;

(c) 'clear air' on the up-link path and 1% worst month conditions on the down-link path.

The table gives values for the *G/T* of the receiving earth station (this changes with down-link rainfall attenuation), the overall *C/N* ratio of the received signal and the Unified *S/N* ratio of the demodulated television signal. The assumptions used in the calculation of these values will be detailed after the table. On the basis that a conventional FM demodulator fails at a *C/N* ratio of 11 dB, all *C/N* entries, and their corresponding *S/N* entries, below this level have been bracketed.

antenna diameter (m)	propagation conditions	receiver *G/T* (dB/K)	*C/N* (dB)	Unified *S/N* (dB)
7	(a)	32.8	[9.4]	[47.2]
	(b)	32.8	[9.2]	[47.0]
	(c)	32.2	[8.3]	[46.1]
8	(a)	34.0	[10.3]	[48.2]
	(b)	34.0	[10.1]	[47.9]
	(c)	33.3	[9.3]	[47.1]
9	(a)	35.0	11.1	48.9
	(b)	35.0	[10.8]	[48.6]
	(c)	34.3	[10.1]	[47.9]
10	(a)	35.9	11.8	49.6
	(b)	35.9	11.4	49.2
	(c)	35.3	[10.8]	[48.6]
13	(a)	38.2	13.3	51.0
	(b)	38.2	12.8	50.5
	(c)	37.5	12.4	50.2
18	(a)	41.0	14.7	52.4
	(b)	41.0	14.0	51.7
	(c)	40.4	14.1	51.8

Assumptions

Up-link transmitter:	Located in the South of England 14.275 GHz operating frequency 72 dBW EIRP at beam centre 0.2 dB mis-pointing loss 25 MHz/V FM deviation sensitivity CCIR Rec. 405 pre-emphasis
Up-link path:	162.7 dBm^2 spreading loss 0.2 dB gaseous attenuation (a) and (c); 0 dB rainfall attenuation (b); 1.1 dB rainfall attenuation
Satellite:	Eutelsat I-F2 Located at 7° East Channel D on Transponder 9 Triple occupancy with Channels B and R (N.B. no ACI)
Sharing signals:	Channel B radiated at 76.6 dBW from beam centre Channel R radiated at 70.6 dBW from beam centre (both with 'clear air' propagation conditions)
Up-link receiver:	1.5 dB/K *G/T* at beam centre 1.4 dB Eurobeam contour loss 80.2 dBW/m^2 IPFD for saturation at beam centre
Down-link transmitter:	10.975 GHz operating frequency 41.5 dBW saturated EIRP at beam centre 1.4 dB Eurobeam contour loss 6 dB input back-off for Channel B 12 dB input back-off for Channel R 12.3 dB input back-off for Channel D in 'clear air' 10.3 dB output back-off for Channel D in 'clear air' 2°/dB AM/PM conversion coefficient for Channel D
Down-link path:	205.0 dB isotropic loss 0.1 dB gaseous attenuation (a) and (b); 0 dB rainfall attenuation (c); 0.7 dB rainfall attenuation
Down-link receiver:	Located in the South of England 65% antenna aperture efficiency 0.2 dB dissipative (feed) loss 0.2 dB non-dissipative (tracking) loss 40 K 'clear air' antenna noise temperature 1.8 dB LNA Noise Figure (149K noise temperature) 39 MHz noise bandwidth 5 MHz video baseband-width CCIR Rec. 405 de-emphasis